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TESTS OF HIGH-SPEED TOOL STEELS ON CAST IRON

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In most manufacturing processes it becomes necessary to change the form of materials in order to bring them to the desired shape for use. Among the metals used in the construction of engineering structures, including the almost endless variety of steam and gas engines, compressors, pumping machinery, marine and locomotive engines, special machinery and machine tools, it is evident that cast iron and steel represent by far the chief constituents of such machines. For the manufacture of all the various parts of these structures and machines there has been designed a great variety of machine tools. In these machine tools are placed the pieces whose shape it is desired to change, and a properly formed and hardened piece of steel is made to cut away a part of the material. The steel used for making the tool for thus cutting the softer material is called Tool Steel. The time required to cut away the necessary amount of metal is an important factor in the cost of the piece under construction. It is evident that the relative hardness of the tool steel and the material it cuts, as well as the speed at which the cutting is attempted, will be important factors in the time required to do the work and of the durability of the tool steel used. These facts have continually exerted a potent influence upon the manufacturers of tool steel and they have constantly improved the qual-

ity of their product. On the other hand, the demand for stronger and lighter materials of construction has increased the density and hardness of many materials already used, and brought into common use new materials, such as cast steel, ferro steel, chilled iron, etc., and these have imposed severer duties on the tool steels designed to cut them. The same rivalry that has existed between armor plate and the projectile intended to pierce it has existed between the tool steels and the materials they are designed to cut. Until quite recently, the rate at which tool steel could cut the various metals was from 10 to 40 feet per minute, varying with the metals cut and with the area of the cross section removed. If a higher rate of cutting was attempted, the point of the tool used became hot, lost its temper and immediately wore away. During the years 1898 to 1900, Messrs. Taylor and White, at the Bethlehem Steel Works, South Bethlehem, Pennsylvania, were seeking to discover what constituents could be combined with tool steel, and what special temperature treatment it should receive that would increase its cutting speed. As the result of their experiments, there was exhibited at the Paris Exposition of 1900 a lathe using a tool steel which removed chips of soft steel at a cutting speed of from 60 to 180 feet per minute. These chips were so hot that they turned blue upon cooling. The point of the tool steel maintained its cutting edge even when running at a dull red glow. It was natural that to such tools should have been given the name of High-Speed Tool Steels.

Properties of Tool Steels

At the time of Taylor and White's first experiments, Mushet and Jessop tool steels of the self-hardening type were in general use. According to Mr. F. Reiser in an article on high-speed steel in "Stahl and Eisen", January 15, 1903, they had the following chemical composition:

Carbon 2.0%	Manganese 2.5%	Silicon 1.3%
Tungsten 5.0%	Chromium 0.5%	

The self-hardening property is called into play by the manganese, an element which favors the combining of the carbon with the iron. These steels were tempered simply by heating to a temperature of 1600° F. and then cooling in air. Mushet and Jessop tools, however, did not prove durable at high speeds, although they were far in advance of the ordinary carbon steels,

and chromium was substituted for manganese with good results. The chromium steels required an entirely different treatment, as was found by Messrs. Taylor and White in their experiments at the Bethlehem Steel Works.

The exact chemical compositions of the new tool steels are secrets of the separate makers, and probably vary; however, it is known that the steels contain the following elements in varying quantities: carbon, tungsten, chromium, manganese, molybdenum and titanium. They usually run high in these combining elements, the Taylor-White steel having as high as 12% of tungsten and 4% of chromium, while Böhler Brothers' Styrian steel, according to Mr. Reiser, has a maximum of 28% of other elements. With this increase the carbon element has greatly decreased; most of it combines with tungsten, chromium and the other elements at high temperatures, remains in that state when cooled in an air blast and forms carbides of extreme hardness and durability at high temperatures. For best results of toughness and hardness these high-speed steels require for tempering a temperature of from 2000° to 2250° F., or a white heat bordering on the fusion point, and are then cooled in an air blast, lead bath or oil bath according to the different makers. Mr. Reiser in his discussion has for this reason correctly named them "superheated steels."

Advantages of High-Speed Steels

High-speed steels, due to their hardness and durability at high temperatures, retain their edge when cutting at extremely high speeds, cases having been noted in which the tool worked at dark-red heat without losing its edge. As can be seen from the tables, the speeds obtained are from three to four times those obtained with ordinary carbon steels. This of course means an increased output for a given shop and a consequent increase in the returns. This is not the only advantage of high-speed steel. It has been proved that such steel is more economical from the power standpoint, a given power removing a greater quantity of metal per unit of time at high speed than at slow speed. Of course the total power required is increased, but the increase is by no means proportional to the increase in the amount of work done.

There is, however, one condition that must be carefully con-

sidered before the introduction of high-speed steels in a shop. Machine tools constructed to use the old carbon steels are limited in capacity and will not stand the heavy stresses to which they would be subjected if using high-speed steels at maximum speeds and feeds. This condition, however, is being met by the machine-tool builders, who are now designing and building especially heavy tools with powerful feed mechanisms with a view towards obtaining the highest possible efficiency of the steel used.

In the following pages are described the experiments made by Mr. H. B. Dirks, Assistant in Mechanical Technology, Engineering Experiment Station, in the shops of the College of Engineering at the University of Illinois. These experiments have been in progress for nearly a year, and every effort has been made to obtain useful and correct results.

For convenience, the subject has been divided into the following parts: I. The Tool Steels Used. II. The Cast-Iron Test Pieces. III. Details of the Tests. IV. Results of the Experiments. V. Summary of Results. VI. Reference List of Articles on High-Speed Steels. Appendix,—giving instructions furnished by makers for hardening the steels used.

I. The Tool Steel Used

(*a*) *The Brands Used*

The following tool steels were used in these trials:

1. Styrian marked "Böhler Rapid"
2. Jessop's "Ark"
3. McInnes's "Extra"
4. Mushet's "Special"
5. "Air Novo"
6. "Rex"
7. "Poldi"
8. "A and W" (Armstrong and Whitworth)

The first six came from the American market. Poldi and "A and W" were furnished by the American Radiator Company, having been used in its foreign factories. With the exception of the Mushet, the steels used were donated for the proposed tests by the makers or agents. The Mushet was taken from stock purchased in the open market. There are doubtless other kinds of steel which could have been tested, but these eight brands were most familiar and accessible to the writers, and it is believed that

they represent fairly well the brands commonly used at the present time by American manufacturers.

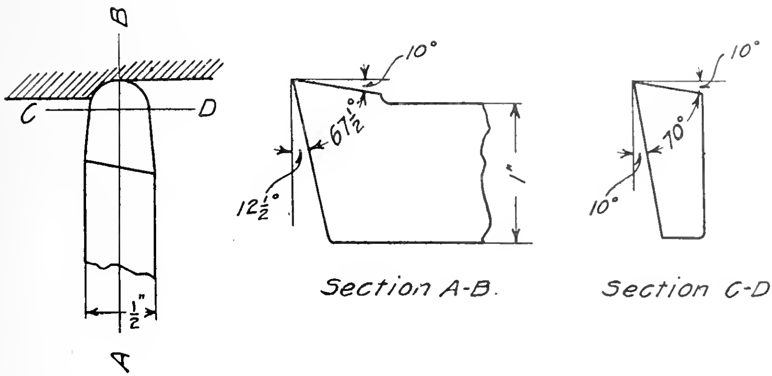


FIG. 4. SHAPE OF CUTTING TOOLS

(*b*) *Size and Shape of Tools*

The size of the bars of steel from which the tools were made was ½ in. by 1 in. for the steels from the American market. The Poldi bar was ¾ in. by 1¾ in., and the "A and W" bar was ¾ in. by 1¼ in. The shape of the tool used in the tests is shown in Fig. 4. The front clearance was 12½°, the top rake was 10° and the side rake was also 10°. These angles were carefully maintained throughout the tests, the angles being measured with a bevel protractor after each grinding.

Experiments relating to the proper shape of tools have been made by Professor J. T. Nicolson,* and the writers were guided in selecting proper tool angles by the recommendations of his paper. Professor Nicolson says: "Tools should therefore be ground for maximum endurance in the cutting of cast iron in ordinary shop practice so that their true cutting angles are about 81°, or if they are allowed 6° clearance for working on the level of the lathe centers, they should have an included angle of about 75°.

(*c*) *Tempering and Tempering Apparatus*

Directions for forging and hardening the various steels used were furnished by the manufacturers. For convenience, these directions are published in the Appendix. It will be seen that most of the steels were to be hardened in an air blast. The "A

*Experiments with a Lathe Tool Dynamometer. See Trans. A. S. M. E., Vol. 25, 1904, page 658 et seq.

and W'' steel was the only one in which oil was recommended for cooling, and then only after the cutting edge of the tool had been cooled to a cherry-red in the air blast. An air blast apparatus was designed and constructed for carrying out the instructions relating to the proper preparation of the tools. This is shown in Fig. 5.

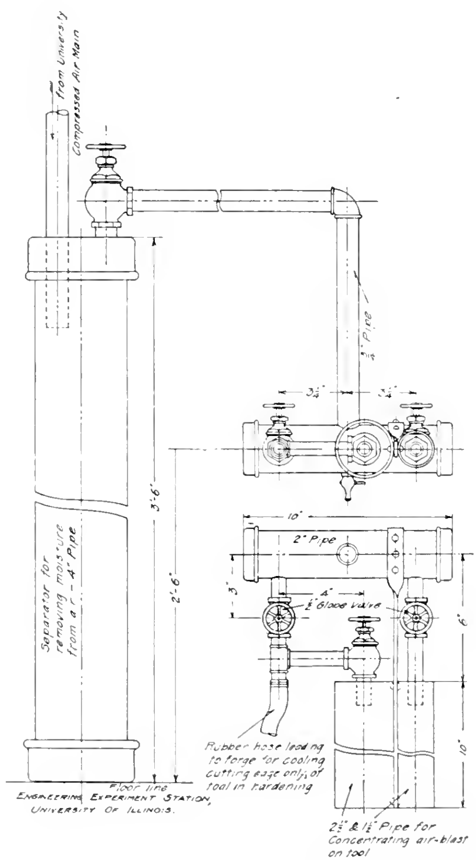


FIG. 5. AIR BLAST APPARATUS

The apparatus consists of the 4-in. separating pipe, 3 ft. 6 in. long to which is connected the header of 2-in. pipe about 10 in. long. The dimensions and construction are shown in the figure. The tools to be hardened are inserted in the short lengths of $1\frac{1}{2}$ or $2\frac{1}{2}$-in. pipes which serve to concentrate the air blast on

the tools. A rubber hose with a $\frac{1}{8}$-in. nozzle in the end is also attached to one opening, so that a strong air blast may be directed on the edge of the tool when first removed from the fire. The tools were heated in an ordinary forge with a clear coke fire. The fire was burned long enough before putting in the tool to drive off any sulphur. Care was also taken to have plenty of coke above and below the tool so that no cold blast should strike the tool while it was being heated.

II. The Cast-Iron Test Pieces

In order that the results of the tests might be of general application, it was advisable that the cast-iron test pieces be the product of several commercial foundries. Several manufacturers throughout the State agreed to furnish sample test pieces representing the grade of cast iron used in their respective foundries. A standard size of test piece was therefore decided upon, and blue prints and patterns of it sent to the different manufacturers. This standard test piece is shown in Fig. 6. The outer diameter is the maximum the lathe will swing over the carriage. This test piece was made hollow for several reasons. A solid test piece becomes soft toward the center and is more likely to contain blow holes. Test pieces of small diameter become springy and consequently produce inaccuracies in the results. The high angular velocity necessary with small diameters is also undesirable. The first test piece used in the preliminary trials was 18 in. long. This was found to be too short, the tool having to be reset too often. In Fig. 3 is given a view of all the test pieces used in the trials. These test pieces do not all conform to the standard test piece, the American Radiator Company having sent test pieces with a 6-in. core instead of a 3-in. core, from several of its plants, that being a more representative casting from its foundries. The test pieces received from the various companies, their identification marks and reference numbers are shown in Table 1.

TABLE 1

RESULTS OF HARDNESS TESTS AND IDENTIFICATION MARKS OF CAST-IRON TEST PIECES USED IN THE TESTS

Name of company sending test pieces		Identification mark	Test reference No.	Hardness by drill test
American Radiator Co. Chicago, Ill.	Pierce plant.	3 " core	3	94.2
			4	109.2
			5	102.0
	Michigan Plant.	5-8-05	6	128.8
			7	86.5
		6 " core	8	94.3
			9	138.6
			10	106.8
			11	109.3
	Detroit plant	D. P. 1	12	100.0
		D. P. 2	13	106.6
		D. P. 3	14	117.2
		D. P. 4	15	132.0
		D. P. 5	16	109.8
		D. P. 6	17	90.3
	——— plant.	5-17-05	18	107.0
			19	117.2
			20	113.9
	——— plant.	B 5-26-05	21	124.8
			22	167.5
			23	122.2
	——— plant.	B 6-2-05	24	111.2
			25	102.4
			26	95.9
Crane Company Chicago, Ill.	Ferro Steel.	F. S.	1	342.0
	Grey Iron.		27	132.0
Root & Vandervoort Eng'g Co...... East Moline, Ill.			2	175.0
University of Illinois.............. Urbana, Ill.		U. I.—1	28	114.5
		U. I.—2	29	195.0
		U. I.—3	30	124.2
		U. I.—4	31	124.5
		U. I.—5	32	123.2

A comparative hardness test was made on all samples, comparison being made with a standard piece of soft cast iron of equal density throughout, the chemical analysis of which is as follows:

Combined Carbon	= .147 %	Silicon	= 2.35 %	Sulphur	= .07 %
Graphite	= 5.03 %	Manganese	= .33 %	Phosphorus	= 1.06 %

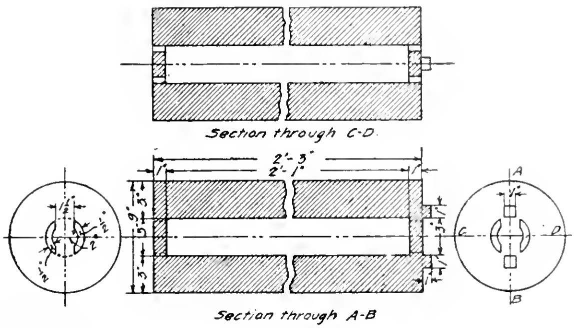


FIG. 6. STANDARD TEST PIECE

The hardness of cast iron or any other metal as indicated by a drill test is probably as fair an indication of the particular quality of the metal that affects the cutting speed as is obtainable by any process in use at the present time. This hardness test is in itself a cutting-speed test in which the cutting speed is not varied, but is held constant and the rate of feed allowed to vary, the cutting speed and rate of feed in all probability bearing some constant relation to each other. Fig. 7 is a graphical chart giving the results of the hardness tests on the test pieces used in the experiments. The tests were made with a drill press as shown in Fig. 8. A constant load of 312 pounds was applied on the spindle of the drill press by means of the weighted lever. With the spindle rotating at a constant speed of 87 r. p. m., the rate of feed of the drill in inches per minute was measured, readings being taken for every $\frac{1}{8}$ in. of depth drilled. The drill used in these tests was a Morse standard $\frac{1}{2}$-in. twist drill ground to an angle of $62\frac{1}{2}°$. As, however, there was some liability of variation in the sharpness of the drill, thus affecting its rate of feed, a uniform piece of cast iron was first drilled into, readings taken, and then the test made on the test piece. A comparison was thus always made with this same piece of cast iron, eliminating any

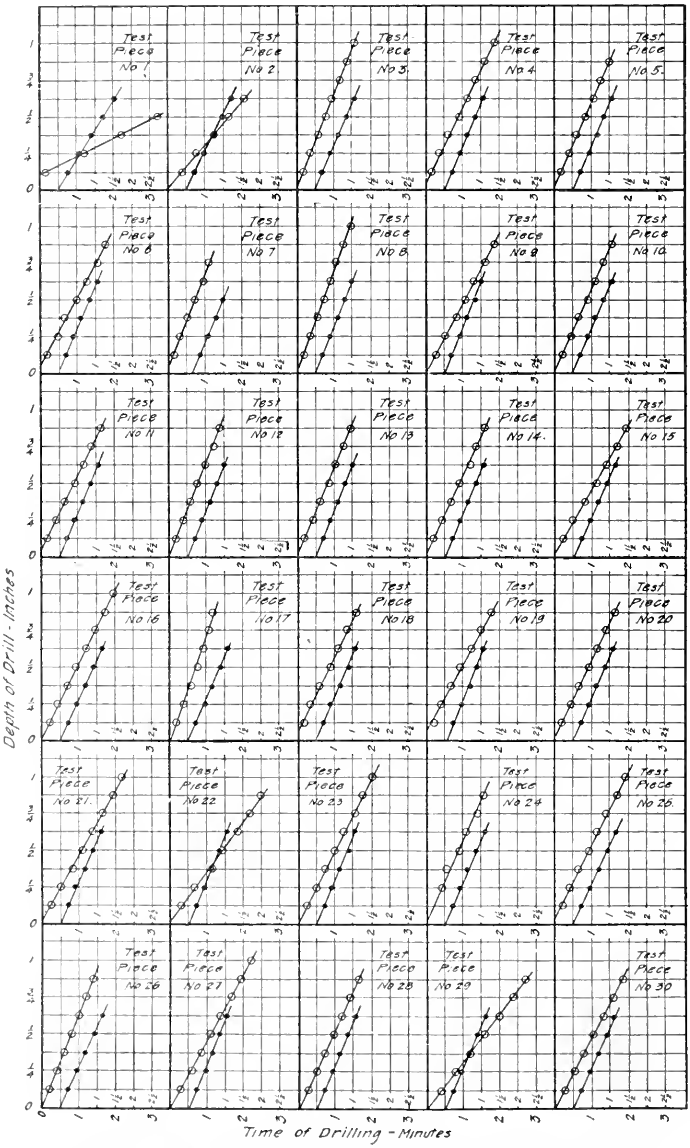


FIG. 7. GRAPHICAL CHART OF HARDNESS DRILL TESTS MADE ON CAST-IRON TEST PIECES

small variation in the sharpness of the drill. In Fig. 7 the curves drawn through the dots represent the standard cast iron, and those drawn through the circles represent the test piece. Thus for test piece No. 1 the rate of feed is about .174 in. per minute, while in drilling the standard cast iron, the rate of feed is about .595 in. per minute. The hardness as used later and as expressed in Table 1 is $\frac{.595}{.174} \times 100 = 342$. Assuming 100 as the hardness of the standard cast iron, Table 1 gives the results obtained from these tests. This method of expressing the hard-

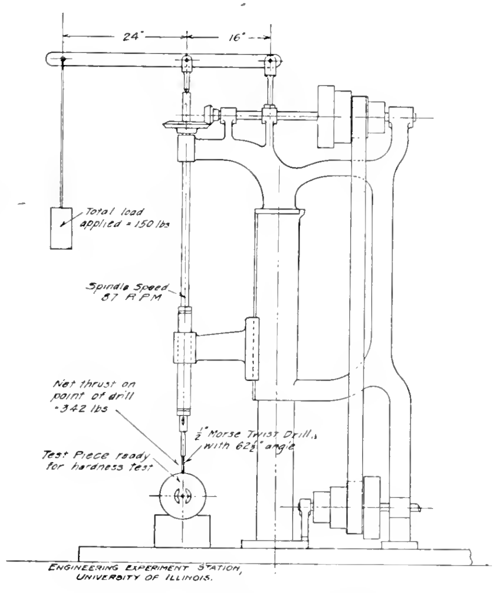


Fig. 8. Drill Press, Showing Method of Making Hardness Tests on Cast-Iron Test Pieces

ness of cast iron was also used by Professor J. T. Nicolson in his experiments with high-speed tool steels made at the Manchester Municipal School of Technology, Manchester, England.* In these experiments the tangent of the angle made by the curve was used as the hardness.

*Report of experiments made at Manchester Municipal School of Technology, London Engineering, October 30 and November 13, 1903.

III. Details of the Tests

(a) Apparatus

The apparatus used in conducting the tests consisted mainly of a high-speed lathe deriving its power from a two-phase induction motor by means of belting and a countershaft. the power required being measured by a polyphase wattmeter. The general arrangement is shown in Fig. 1 and Fig. 9. The lathe used (see Fig. 2 and Fig. 10) was a Pratt and Whitney high-speed lathe with a gear box head-stock, taking a maximum length of 3 ft. 9

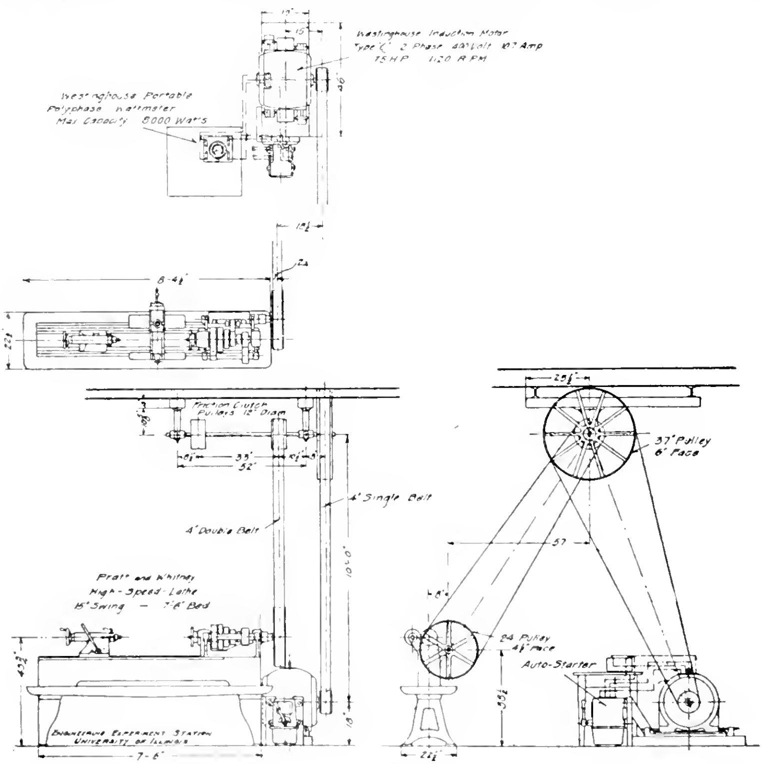


Fig. 9. General Arrangement of Apparatus used in the Tests with High-Speed Tool Steels

in. between centers and a diameter of 9 in. over the carriage. The power was transmitted from the first motion shaft of the head-stock to the cone gears by means of a long pinion and an intermediate gear, the latter being fastened to the intermediate

gear frame which swivels about the first motion shaft. The intermediate gear frame has a substantial slide with rack, pinion and crank by which the intermediate gear is moved to any one of four positions, in which it is locked by the dropping of a pin into suitable holes in the frame, after which movement the frame is swiveled to drop the gear into mesh with the cone gear. The latch handle at each end of the frame holds the frame and gears in position after the gears are in mesh. From the cone gears the power is transmitted either direct to the spindle or through the usual back gears, thus making 8 changes of speed. The speeds and feeds obtainable are shown in Table 2 and Table 3. The feed mechanism is positive, being driven by two gears from the main spindle through a chain of gears to the feed box change and speed gears, thence through the feed rod to the carriage. There are 8 changes possible both for the cross and longitudinal feed. A reverse feed is obtained by shifting the reverse rod.

TABLE 2

FEEDS AND FEED GEARS FOR

PRATT & WHITNEY HIGH-SPEED LATHE

Feeds	Feed Gears	Change Gears	Feed Box Change Gears	Feed Box Speed Gear	Worm	Apron Feed Gear	Rack Pinion	Cross Feed Screw	Feed per one Rev. of Spindle	Rev. of Spindle to 1" Travel
Longitudinal Feed	44 to 88 Forward 42 to 84 Reverse, 28 Intermediate	39 to 78 Outside Change Gears 2–78 Intermediate	48 to 64	38 to 74		22 to 66	18 t–8 P.		.0076	131.6
			60 to 52						.0116	86.2
			68 to 44						.0156	64.1
			78 to 34						.0232	43 1
			48 to 64	76 to 36					.0312	32.0
			60 to 52						.0478	20.9
			68 to 44						.0642	15.6
			78 to 34						.0952	10.5
Cross Feed			48 to 64	38 to 74		76 to 18 with 49 Intermediate		$\frac{1}{8}$ lead single	.00508	196.8
			60 to 52						.00782	127.7
			68 to 44						.01045	95.7
			78 to 34						.01554	64.3
			48 to 64	76 to 36					.0209	47.8
			60 to 52						.0322	31.1
			68 to 44						.0431	23.2
			78 to 34						.0640	15.6

TABLE 3

RANGE OF SPEED RATIOS AND SURFACE SPEEDS FOR APPARATUS USED IN HIGH-SPEED STEEL TESTS

Motor Pulley Diameter (1120 r. p. m.)	Revolutions per minute				Surface speed of test piece. Feet per min.	
	Counter-shaft	Lathe Pulley	Lathe Spindle			
			Direct drive	Drive through back gears	Direct drive	Drive through back gears
6 inches	181.62	90.81	68.10 45.40 34.05 27.24	23.48 15.65 11.74 9.38	160.37 106.92 80.19 64.15	55.30 36.80 27.65 22.09
7 inches	211.89	105.94	79.46 52.97 39.73 31.78	27.40 18.26 13.70 10.95	187.10 124.70 93.56 74.84	64.53 43.00 32.26 25.79
8 inches	242.16	121.08	90.81 60.54 45.41 36.32	31.31 20.87 15.65 12.52	213.80 142.60 106.90 85.53	73.74 49.15 36.86 29.48
9 inches	272.43	136.21	102.16 68.11 51.08 40.86	35.23 23.48 17.61 14.10	240.60 160.40 120.30 96.23	82.97 55.30 41.47 33.21
10 inches	302.70	151.30	113.50 75.65 56.74 45.39	39.13 26.10 19.56 15.65	267.30 178.20 133.60 106.90	92.15 61.47 46.06 36.86
11 inches	332.97	166.48	124.90 83.24 62.43 49.94	43.07 28.73 21.52 17.12	294.10 196.00 147.00 117.60	101.40 67.66 50.68 40.32
12 inches	363.24	181.62	136.20 90.81 68.11 54.49	46.96 31.31 23.48 18.78	320.80 213.80 160.40 128.30	110.60 73.74 55.30 44.23

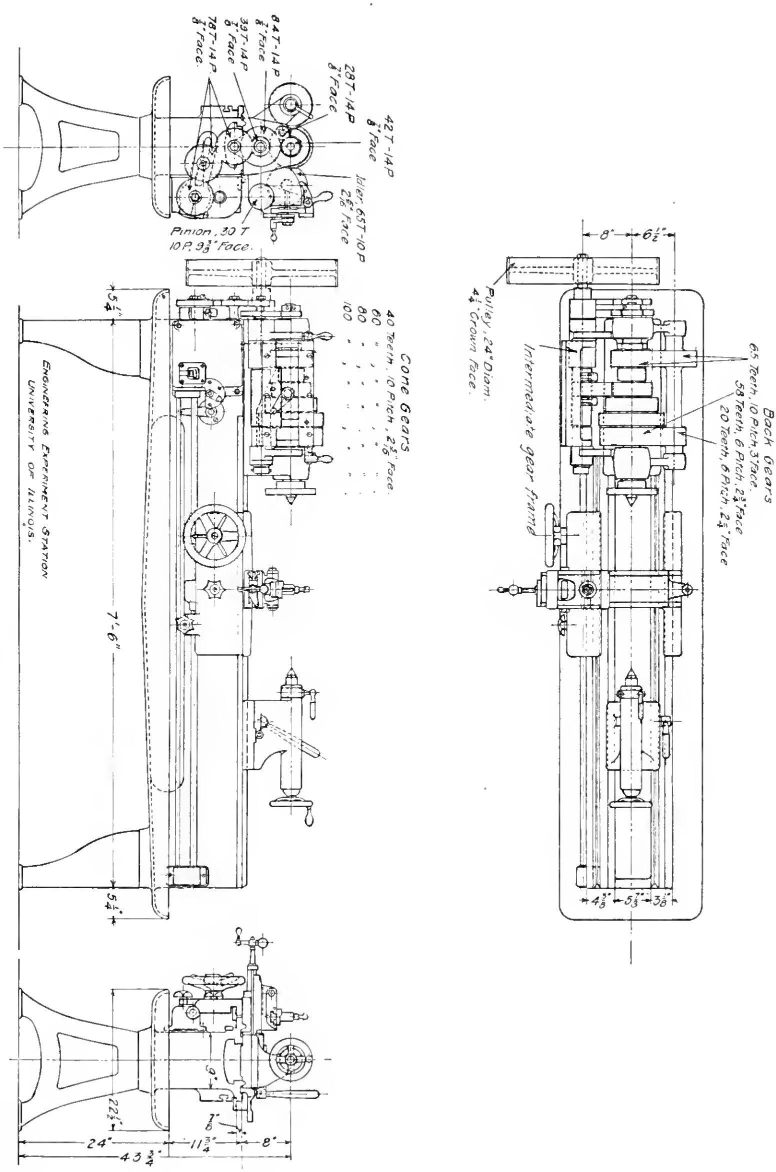


FIG. 10. LATHE USED IN THE TESTS WITH HIGH-SPEED TOOL STEELS

The power was transmitted to the lathe by means of a 4-in. double belt from the 12-in. friction clutch pulley of the countershaft. The countershaft in turn was driven through a 37-in. pulley by a 4-in. single belt from the motor. The motor is on an adjustable base, allowing changes of the motor pulley to be made without changing the length of the belt. In the tests, pulleys ranging from 6 to 12 in. in diameter were used, making possible with the 8 changes of speed on the lathe proper, 56 changes for every diameter of work. As the diameter of the test piece decreased, it was thus possible to keep the speed of the cut constant within very small limits. The motor received its current from the 440 volt main of the University power plant. As shown in Fig. 9, the current passed through an auto-starter and wattmeter into the motor, the auto-starter being used to reduce the electromotive force on the motor at starting, thus diminishing the liability of injury to the motor.

The wattmeter used is known as the Westinghouse portable long scale indicating wattmeter for alternating current circuits, and may be used for either two, three or four-phase circuits. "In principle, the wattmeter consists of a miniature induction motor, having for an armature a metal drum mounted on a shaft, together with a spring and pointer, giving indications on the scale proportional to the power to be measured. There is also a stationary circular core of iron inside the drum to complete the magnetic circuit through the armature As it operates on the induction principle, it has no moving wires and is not affected by external fields." "The polyphase wattmeter used in the tests is a modification of the above, having two drums mounted on the same shaft and revolving in two separate fields. This construction makes a meter which is correct for two or three-phase circuits under all conditions of unbalancing, low power factor, etc., and measures the true energy of the circuit".*

(*b*) *Procedure in Making the Tests*

In the preliminary trials the skin was first removed to bring the test piece to a uniform diameter throughout. This was discontinued in the later trials and a separate series of skin cut trials was run. The test piece having been made ready for the test, the tool to be used was placed in the tool rest in the position

*Taken from instructions for the use of the W. P. L. S. I. Wattmeters.

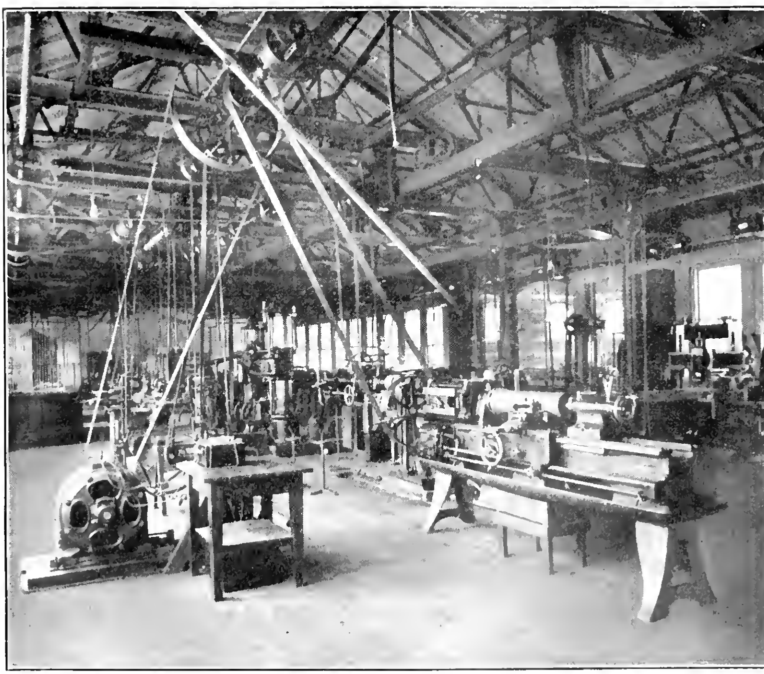


Fig. 1 View in the University of Illinois Machine Shop showing location of Lathe and Motor drive used in Tests with High-Speed Tool Steels

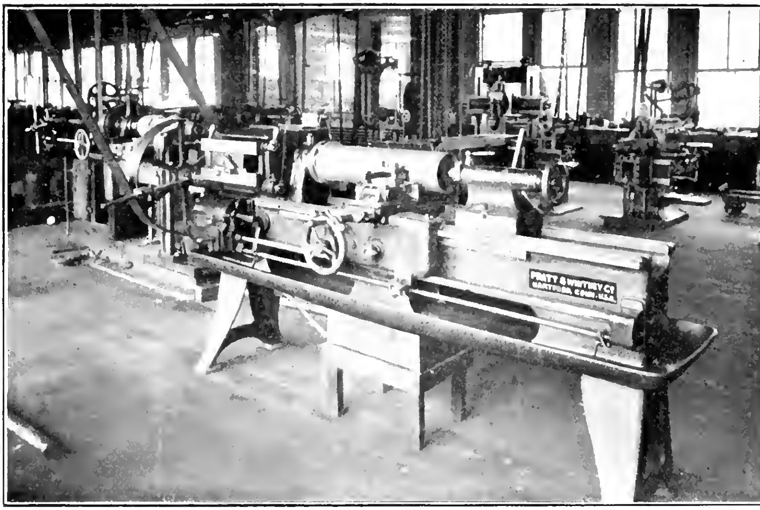


Fig. 2. Lathe used in Tests with High-Speed Tool Steels

Fig. 3. Cast-Iron Test Pieces used in Tests with High-Speed Tool Steels

decided upon for all tools and trials, viz., at right angles to the work with the bottom edge of the tool horizontal and the cutting edge of the tool from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. above the center of the work, its exact position being recorded in the log. The diameter of the test piece was then accurately measured in several places and the average recorded in the log. The tool was then fed in by hand until the cutting edge just scraped the bottom of the groove left by the last turning. The graduated disc on the cross feed having been set at zero, with the tool in the above position, the cross feed was turned back a little, and the carriage moved to the right sufficiently for the tool to clear the test piece. The cross feed was then advanced until the graduated disc showed the required cut opposite the index mark. The longitudinal feed or traverse was then set in position and recorded in the log. The diameter of the work and the surface speed required during the trial being known, the size of the pulley to be used on the motor and the position of the driving gear necessary to give the required speed were obtained from a set of curves giving the speed for various diameters of work for each of the 56 changes obtainable. This having been done, the lathe was started and the surface speed tested with a Warner cutmeter. If found to be too far from the required speed, a different combination of motor pulley and cone gear was tried. A satisfactory speed having been obtained, the feed mechanism was started and the lathe allowed to run until the tool had entered the work and was taking the full cut. The lathe was then stopped and the square-case revolution counter, which was actuated by the first motion shaft, set at zero. The lathe was then cleared of all chips and the test started, the exact time of starting and the position of the revolution counter being recorded. During the trials, readings of the revolution counter and also of the wattmeter were taken every two minutes in order to obtain any variations in the cutting speed and the power required. After the expiration of the trial, which occurred either at the time of failure of the tool or at a specified time limit, the tool was withdrawn and the lathe run light under the same conditions of speed as in the trials, in order to observe the electrical horse-power exerted by the motor under these conditions. All cuttings were then collected, weighed and recorded in the log. To facilitate the collection of chips, sheet iron guards were placed on the bed of the lathe.

(c) *Description of Methods Adopted for Measuring the Force Required in Cutting*

During the trials readings were taken at regular intervals of the total electrical watts input in the motor, while cutting, and after the tool had been withdrawn, with the lathe running light. The difference between the electrical horse-power with the tool cutting and with the lathe running without the cut should give the net horse-power required for cutting, and if this be multiplied by 33,000 and divided by the cutting speed, we obtain the force required for cutting in pounds. In thus figuring, we assume that the lost horse-power of the drive remains constant from no load to full load. To determine whether or not this was the case, a Prony brake was placed on the cast-iron test piece, as shown in Fig. 11. This could be made to offer the resistance otherwise produced by the cutting tool, and this resistance could be meas-

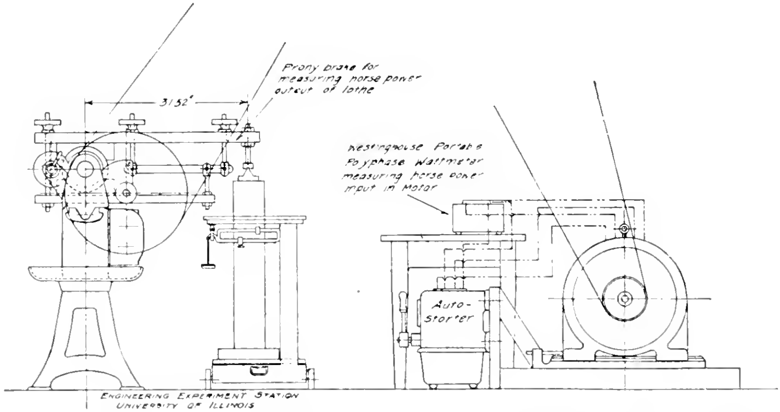


Fig. 11. Arrangement of Apparatus for Measuring Power Absorbed by Friction in the Lathe, Countershaft and Belting

ured at the end of the brake arm by observing the reading on the scale beam of the platform scales. The brake arm was made 31.52 in. in length to facilitate the work of obtaining the horse-power, which would then be $\frac{PN}{2000}$, in which P is the net thrust on the scale in pounds and N the number of revolutions of the brake wheel.

Experiments were made on the lathe for both methods of driving it, either direct or through the back gearing. The results

of these experiments are given in Fig. 12. In the same figure is also shown the calibration curve for the motor alone, giving the horse-power output for a known input. The loss in the transmission for any known input could be immediately found, it

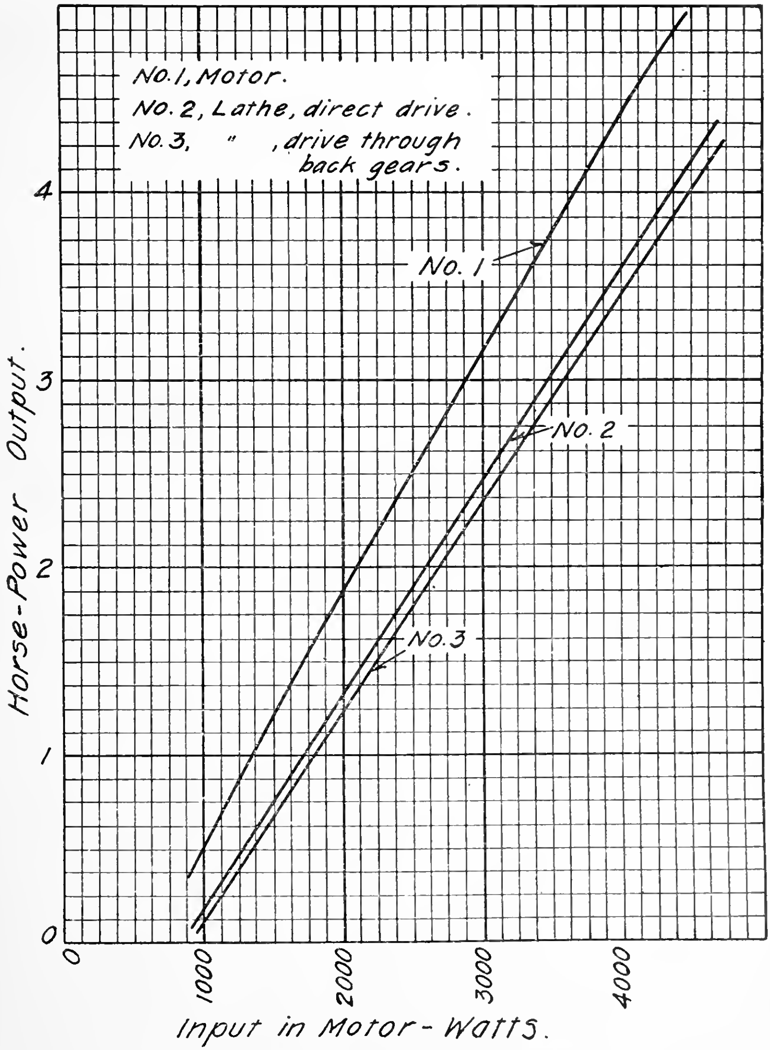


FIG. 12. CURVES GIVING RESULTS OF EXPERIMENTS TO DETERMINE LOSS OF POWER IN LATHE AND COUNTERSHAFT FOR VARYING LOADS

being the vertical distance between the curves at the required load. From the curves it can be seen that it is not constant, but increases at a constant ratio as the load increases. The equations derived from the curves, giving the relation between the net and gross load for both drives, are as follows:

(1) $N = 0.886G - 0.32$ (2) $N = 0.907G - 0.41$

Where N = net horse-power required for cutting, at the tool point, represented in Fig. 12 by the ordinates of the curves No. 2 and No. 3 according as the lathe is running with or without the back gears; and

G = total horse-power output of motor, represented in Fig. 12 by the ordinates of curve No. 1.

In these equations, (1) applies to the direct drive, and (2) to the drive through the back gears. The net horse-power recorded in Tables VI to X under column 6 contains the above-found correction. The nature of the results will be discussed in Part IV.

IV. Results of the Experiments

The results of the tests made with the eight brands of steel are given in full in Tables I to X below. Some of the most important relations are shown graphically on several plates. There were in fact five sets of experiments made which may properly be referred to as:

(a) The preliminary trials
(b) The skin-cut trials
(c) The endurance trials
(d) Trials to obtain the durability of the steels at different cutting speeds for various sizes of cut, but on cast iron of constant hardness
(e) Trials to obtain the durability of the steels on cast iron of varying hardness.

Tables I to V give for each of the experiments above referred to the observed and calculated data indicated in the 18 columns of results. Some of the most important results given in these tables are:

(a) The cutting speed in feet per minute
(b) The area of section cut
(c) The area machined
(d) The weight of material removed per minute
(e) The relative durability of the tool
(f) The hardness of the test piece

In the same way Tables VI to X give important data for each one of the sets of experiments carried out. The most interesting results which are given by these tables are:

(a) The cutting force on the point of the tool
(b) The net horse-power required to remove the metal
(c) The horse-power required to run the lathe and the countershaft

The headings for the different tables are for the most part clearly indicated. It may be advisable, however, to explain some of them more fully. Referring to Tables I to V, we have in each table the same 18 headings. Columns 4, 5 and 6 give the speeds, cuts and feeds at which the trials were intended to be carried out, as calculated from the size of the pulleys and motor speeds. In columns 7, 8 and 9 are given the actual speeds, cuts and feeds. The cutting speed recorded is the speed in feet per minute of the cylindrical surface of maximum diameter at the point of cutting. The depth of cut is one-half the difference of the diameters of the work before and after cutting. The feed is the advance of the tool per revolution of lathe spindle. Column 10 gives as the area of the section cut the product of the depth of cut and the feed. Columns 12 and 13 give the area of the surface machined. This was obtained by multiplying the cutting speed in feet per minute by the feed in feet per revolution of the spindle. Columns 14 and 15 give the total weight of cuttings removed during the trial and also per minute. These results were obtained by collecting and weighing the cuttings. Column 17 gives the comparative durability of the tool. An entirely arbitrary standard of durability was established as follows: A tool whose cutting edge was worn away .002 in. after one hour's use was considered perfect, its durability being expressed as 100. The ratios of the durability of any other tools to the standard will then be the inverse of the ratios of their rates of wear to the rate of wear of the standard. The wear as assumed for the standard is shown in Figure 13 at x. In the experiments, however, the distance a was measured and x then calculated.

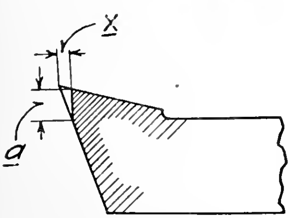


FIG. 13.

TABLE I

Experiments with High-Speed Tool Steel on Cast Iron

Preliminary Trials

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended		Actual	Actual		Area of Sec. of cut	Duration of Trial
			Speed	Cut & Feed	speed	Cut	Feed		
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Styrian	28	3	55	$\frac{3}{8}$x$\frac{3}{128}$	54.8	$\frac{3}{8}$	.0232	.00870	33
2 "	28	4	35	$\frac{1}{2}$x$\frac{1}{32}$	36.2	$\frac{1}{2}$	.0312	.01560	31
3 "	28	5	30	$\frac{1}{4}$x$\frac{1}{16}$	32.5	$\frac{1}{4}$	.0642	.01600	15$\frac{5}{6}$
4 "	28	6	60	$\frac{1}{8}$x$\frac{3}{32}$	60.5	$\frac{1}{8}$	.0952	.01190	5
5 "	28	7	60	$\frac{1}{8}$x$\frac{1}{16}$	59.6	$\frac{1}{8}$	.0642	.00802	7$\frac{1}{3}$
6 "	28	8	60	$\frac{1}{8}$x$\frac{1}{32}$	58.0	$\frac{1}{8}$	.0312	.00390	10
7 "	28	9	50	$\frac{3}{8}$x$\frac{1}{32}$	52.1	$\frac{3}{8}$	.0312	.01160	15
8 "	28	10	50	$\frac{3}{8}$x$\frac{1}{32}$	47.6	$\frac{3}{8}$	.0312	.01160	8
9 "	28	11	40	$\frac{1}{4}$x$\frac{1}{32}$	41.2	$\frac{1}{4}$	.0312	.00780	8
10 McInnes	1	23	30	$\frac{1}{8}$x$\frac{1}{16}$	28.4	$\frac{1}{8}$	.0642	.00802	10
11 "	1	24	30	"	31.8	$\frac{1}{8}$	.0642	.00802	10
12 "	1	25	30	"	31.9	$\frac{1}{8}$	.0642	.00802	10
13 Novo	1	27	40	$\frac{1}{16}$x$\frac{1}{16}$	40.7	$\frac{1}{16}$	.0642	.00401	22
14 "	1	28	40	"	43.7	$\frac{1}{16}$	.0642	.00401	16
15 "	1	29	40	"	42.5	$\frac{1}{16}$	.0642	.00401	19
16 Styrian	1	30	40	"	41.3	$\frac{1}{16}$	.0642	.00401	13$\frac{1}{2}$
17 Novo	1	31	40	"	41.7	$\frac{1}{16}$	.0642	.00401	13
18 Styrian	27	130	150	$\frac{1}{8}$x$\frac{1}{32}$	152.1	$\frac{1}{8}$	.0312	.00390	11$\frac{1}{2}$
19 Novo	27	131	150	"	153.1	$\frac{1}{8}$	.0312	.00390	9
20 McInnes	27	132	150	"	150.0	$\frac{1}{8}$	.0312	.00390	1$\frac{1}{2}$
21 Styrian	16	133	110	$\frac{3}{16}$x$\frac{1}{16}$	111.0	$\frac{3}{16}$	.0642	.01200	7
22 Novo	16	134	105	$\frac{1}{8}$x$\frac{1}{16}$	107.2	$\frac{1}{8}$	.0642	.00802	12$\frac{1}{3}$
23 Styrian	23	135	130	$\frac{1}{8}$x$\frac{1}{32}$	133.8	$\frac{1}{8}$	.0312	.00390	4$\frac{2}{3}$
24 "	23	136	130	"	134.3	$\frac{1}{8}$	.0312	.00390	2$\frac{1}{5}$
25 "	23	137	100	"	102.9	$\frac{1}{8}$	.0312	.00390	17$\frac{1}{2}$
26 Novo	23	138	100	"	106.3	$\frac{1}{8}$	.0312	.00390	1$\frac{1}{3}$
27 "	22	139	100	"	101.5	$\frac{1}{8}$	.0312	.00390	6$\frac{2}{3}$
28 Styrian	22	140	80	"	79.5	$\frac{1}{8}$	.0312	.00390	8
29 Jessop	31	141	50	$\frac{1}{8}$x$\frac{1}{16}$	53.3	$\frac{1}{8}$	.0642	.00802	13$\frac{1}{3}$
30 "	31	142	75	"	75.2	$\frac{1}{8}$	.0642	.00802	14$\frac{3}{4}$
31 "	32	143	85	"	85.0	$\frac{1}{8}$	.0642	.00802	22$\frac{1}{2}$

TABLE I—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Styrian..........	3.53	.107	43.60	1.320	Time up	100.00	114.5
2 "	2.92	.094	50.50	1.630	"	50.50	114.5
3 "	2.67	.169	24.20	1.530	"	12.90	114.5
4 "	2.36	.472	10.30	2.060	"	100.00	114.5
5 "	2.27	.310	9.82	1.340	"	100.00	114.5
6 "	1.51	.151	6.81	.681	"	100.00	114.5
7 "	.20	.135	25.90	1.730	"	100.00	114 5
8 "	.99	.124	12.20	1.530	"	100.00	114.5
9 "	.85	.107	6.74	.843	"	100.00	114.5
10 McInnes.........	1.51	.151	6.43	.643	"	2.03	342.0
11 "	1.70	.170	7.00	.700	Tool failed	0.00	342.0
12 "	1.70	.170	7.37	.737	Time up	4.07	342.0
13 Novo	4.77	.217	11.80	.539	"	6.52	342.0
14 "	3.72	.233	8.67	.542	"	6.93	342.0
15 "	4.31	.227	10.30	.541	"	4.90	342.0
16 Styrian..........	2.98	.221	7.26	.538	"	5.50	342.0
17 Novo	2.90	.223	6.99	.538	"	5.30	342.0
18 Styrian..........	4.54	.395	.....	.....	Tool failed	3.12	132.0
19 Novo	3 58	.398	.....	.....	"	0.10	132.0
20 McInnes.........	.40	.390	.....	.... .	"	0.00	132.0
21 Styrian..........	4.16	.594	28.75	4.107	"	0.00	109.8
22 Novo	7.16	.573	32.20	2.580	Time up	5.09	109.8
23 Styrian....	1.61	.347	7.08	1.520	Tool failed	0.00	122.2
24 "	.75	.349	3.28	1.520	"	0.00	122.2
25 "	4.67	.267	21.20	1.210	Time up	3.56	122.2
26 Novo	.....	.....	.....	.....	Tool failed	0.00	122.2
27 "	1.76	.264	9.12	1.370	"	0.00	167.5
28 Styrian..........	1.65	.206	8.72	1.090	"	0.00	167.5
29 Jessop	2.76	.282	17.20	1.290	Time up	100.00	124.5
30 "	5.92	.402	26.50	1.800	"	100.00	124.5
31 "	10.20	.454	45.60	2.030	"	18.30	124.5

TABLE II

Experiments with High-Speed Tool Steel on Cast Iron

Skin-Cut Trials

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended		Actual speed	Actual		Area of Sec. of cut	Duration of Trial
			Speed	Cut & Feed		Cut	Feed		
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Styrian .	28	1	45	$\frac{7}{32}$x$\frac{3}{128}$	45.2	$\frac{7}{32}$	.0232	.00507	$9\frac{1}{2}$
2 Styrian.	28	2	35	"	36.3	$\frac{7}{32}$	.0232	.00507	39
3 McInnes	29	12	45	$\frac{1}{4}$x$\frac{1}{64}$	46.2	$\frac{1}{4}$	.0156	·00390	30
4 McInnes	29	13	60	$\frac{1}{4}$x$\frac{1}{32}$	59.5	$\frac{1}{4}$	.0312	·00780	$6\frac{1}{2}$
5 McInnes	29	14	35	$\frac{1}{4}$x$\frac{1}{64}$	36.4	$\frac{1}{4}$	.0156	.00390	40
6 Styrian..	3	97	50	$\frac{3}{16}$x$\frac{1}{32}$	50.6	$\frac{3}{16}$	.0312	.00585	40
7 Styrian.	6&7	98	55	"	55.2	"	.0312	.00585	$72\frac{1}{2}$
8 Novo ...	8	99	55	"	55.0	"	.0312	.00585	36
9 McInnes	9	100	55	"	57.4	"	.0312	.00585	35
10 Novo....	10	101	55	"	55.5	"	.0312	.00585	35
11 McInnes	11	102	55	"	54.4	"	.0312	.00585	37
12 Poldi. .	12&13	103	55	"	55.6	"	.0312	.00585	72
13 A. & W.	14	104	55	"	55.3	"	.0312	.00585	$29\frac{1}{2}$
14 A. & W.	4	105	55	"	56.0	"	.0312	.00585	37
15 Styrian..	5	106	70	"	67.9	"	.0312	.00585	30
16 Novo...	18	107	70	$\frac{1}{8}$x$\frac{1}{32}$	68.8	$\frac{1}{8}$	.0312	.00390	21
17 McInnes	19	108	70	"	68.5	"	.0312	.00390	$8\frac{1}{2}$
18 McInnes	19	109	70	"	68.5	"	.0312	.00390	10
19 Poldi...	20	110	70	"	68.0	"	.0312	.00390	19
20 Novo...	20	111	70	"	68.2	"	.0312	.00390	11
21 Styrian.	17	112	75	"	75.3	"	.0312	.00390	27
22 Novo...	26	113	75	"	75.2	"	.0312	.00390	27
23 McInnes	25	114	75	"	75.7	"	.0312	.00390	27
24 Poldi...	16	115	75	"	74.7	"	.0312	.00390	$26\frac{1}{2}$
25 A. & W.	24	116	75	"	73.9	"	.0312	.00390	$27\frac{5}{6}$
26 Styrian.	23	117	75	"	72.2	"	.0312	.00390	28
27 Poldi...	21	118	75	"	75.0	"	.0312	.00390	27
28 A. & W.	15	119	75	"	74.2	"	.0312	.00390	27
29 McInnes	22	120	75	"	73.8	"	.0312	.00390	$19\frac{1}{4}$
30 Styrian.	22	121	75	"	72.5	"	.0312	.00390	$8\frac{1}{2}$
31 Jessop..	32	122	45	$\frac{1}{4}$x$\frac{1}{32}$	46.1	$\frac{1}{4}$	.0312	.00780	28

TABLE II—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Styrian	0 83	.088	4.6	.488	Tool failed	0.00	114.5
2 Styrian..........	2.76	.070	14.4	.370	Time up	7.94	114.5
3 McInnes.........	1.81	.060	14.4	.480	"	6.12	195.0
4 McInnes.........	0.99	.155	7.1	1.105	Tool failed	5.23	195.0
5 McInnes.........	1.89	.047	14.7	.367	Time up	8.16	195.0
6 Styrian..........	5.24	.131	29.8	.746	"	100.00	94.2
7 Styrian..........	1.04	.143	57.2	.789	"	14.80	107.6
8 Novo............	5.15	.143	23.3	.648	"	5.85	94.3
9 McInnes.........	5.21	.149	24.5	.702	"	5.70	138.6
10 Novo............	5.04	.144	33.5	.958	"	14.30	106.8
11 McInnes.........	5.22	.141	30.0	.812	"	10.00	109.3
12 Poldi............	10.40	.144	67.7	.941	"	17.85	103.3
13 A. & W..........	4.25	.144	29.8	1.012	"	24.00	117.2
14 A. & W..........	5.36	.145	35.6	.964	"	15.00	109.2
15 Styrian..........	5.28	.176	34.2	1.140	"	12.20	102.0
16 Novo............	3.76	.179	30.8	1.470	"	4.28	107.0
17 McInnes	1.51	.178	.....	.....	Tool failed	0.00	117.2
18 McInnes.........	1.78	.178	.....	.....	Time up	8.13	117.2
19 Poldi............	3.36	.177	21.0	1.110	Tool failed	0.00	113.9
20 Novo............	1.95	.177	12.1	1.110	Time up	2.23	113.9
21 Styrian..........	5.29	.196	24.4	.903	"	22.00	90.3
22 Novo............	5.26	.195	19.0	.704	"	7.33	95.9
23 McInnes.........	5.32	.197	23.0	.852	"	11.00	102.4
24 Poldi.....	5.14	.194	22.5	.850	"	10.80	109.8
25 A. & W..........	5.34	.192	24.6	.887	"	11.35	111.2
26 Styrian..........	5.23	.187	22.6	.808	"	7.61	122.2
27 Poldi............	5.26	.195	19.1	.708	"	5.50	124.8
28 A. & W........ ..	5.21	.193	28.4	1.050	"	22.00	107.0
29 McInnes.........	3.70	.192	14.5	.756	Tool failed	00.00	167.5
30 Styrian..........	1.60	.188	.....	.....	Time up	3.46	167.5
31 Jessop..........	3.36	.120	27.5	.982	"	22.80	123.2

TABLE III

Experiments with High-Speed Tool Steel on Cast Iron

Endurance Trials

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended Speed	Intended Cut & Feed	Actual Speed	Actual Cut	Actual Feed	Area of Sec. of cut	Duration of Trial
			Ft. Min.	Ins.	Ft. Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Novo. . .	29	15	50	$\frac{1}{2}$x$\frac{1}{64}$	47.6	$\frac{1}{2}$	.0156	.00780	68
2 Styrian .	30	17	50	"	48.3	$\frac{1}{2}$	.0156	.00780	161
3 McInnes	30	18	50	"	52.4	$\frac{1}{2}$	.0156	.00780	120
4 Jessop. .	31	124	75	$\frac{1}{4}$x$\frac{1}{32}$	76.9	$\frac{1}{4}$	.0312	.00780	51
5 Novo. . .	29	16	40	$\frac{1}{2}$x$\frac{1}{32}$	37.6	$\frac{1}{2}$	.0312	.01560	107$\frac{1}{2}$
6 McInnes	27	19	75	$\frac{1}{8}$x$\frac{1}{32}$	77.8	$\frac{1}{8}$	.0312	.00390	181
7 Novo. . .	27	20	75	"	75.5	$\frac{1}{8}$	.0312	.00390	88$\frac{1}{12}$
8 Styrian .	3	36	65	"	63 6	$\frac{1}{8}$	.0312	.00390	195$\frac{1}{2}$
9 McInnes	3	37	65	"	67.7	$\frac{1}{8}$	.0312	.00390	181$\frac{1}{2}$
10 Novo. . .	3	38	65	"	67.1	$\frac{1}{8}$	.0312	.00390	40$\frac{1}{2}$
11 Styrian .	1	21	30	$\frac{1}{8}$x$\frac{1}{16}$	28.0	$\frac{1}{8}$	.0642	.00802	98$\frac{1}{2}$
12 Novo. . .	1	22	30	"	27.7	$\frac{1}{8}$	.0642	.00802	97$\frac{1}{4}$
13 Novo. . .	2	34	50	"	51.1	$\frac{1}{8}$	.0642	.00802	153$\frac{1}{2}$
14 Styrian .	2	35	50	"	53.2	$\frac{1}{8}$	.0642	.00802	127
15 Jessop. .	31	123	75	"	74.5	$\frac{1}{8}$	.0642	.00802	47$\frac{1}{3}$
16 Rex. . . .	32	126	80	"	80.4	$\frac{1}{8}$	.0642	.00802	55
17 Styrian..	12	45	85	$\frac{1}{8}$x$\frac{3}{32}$	88.7	$\frac{1}{8}$	.0952	.01190	49$\frac{3}{4}$
18 McInnes	14	47	90	"	92.4	$\frac{1}{8}$	.0952	.01190	15$\frac{1}{2}$
19 Novo....	13	46	95	"	97.7	$\frac{1}{8}$	.0952	.01190	48$\frac{1}{6}$
20 Poldi....	14	48	105	"	105.2	$\frac{1}{8}$	.0952	.01190	17$\frac{1}{3}$
21 A. & W.	14	49	115	"	113.6	$\frac{1}{8}$	.0952	.01190	17$\frac{1}{2}$
22 Styrian..	1	26	35	$\frac{1}{16}$x$\frac{1}{16}$	38.7	$\frac{1}{16}$	.0642	.00401	88
23 McInnes	1	32	35	"	36.1	$\frac{1}{16}$	.0642	.00401	64$\frac{1}{2}$
24 Styrian..	1	33	35	"	36.6	$\frac{1}{16}$	.0642	.00401	58$\frac{1}{2}$
25 Rex.....	32	125	85	"	84.5	$\frac{1}{16}$	.0642	.00401	62$\frac{1}{2}$
26 Styrian..	6& 7	39	75	$\frac{1}{16}$x$\frac{3}{32}$	76.6	$\frac{1}{16}$	.0952	.00595	125
27 Novo. . .	7& 8	40	75	"	74.3	$\frac{1}{16}$	.0952	.00595	119$\frac{1}{2}$
28 McInnes	8& 9	41	75	"	77.5	$\frac{1}{16}$	.0952	.00595	130
29 Poldi . . .	9& 10	42	75	"	77.4	$\frac{1}{16}$	.0952	.00595	128
30 A. & W.	10& 11	43	75	"	75.0	$\frac{1}{16}$	.0952	.00595	122$\frac{1}{2}$
31 Mushet .	11	44	75	"	74.6	$\frac{1}{16}$	.0952	.00595	42$\frac{1}{2}$

TABLE III—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Novo	4.2	.062	71.9	1.058	Time up	27.6	195.0
2 Styrian	10.1	.062	182.0	1.132	"	100.0	124.2
3 McInnes	8.2	.068	130.0	1.087	"	100.0	124.2
4 Jessop	10.2	.200	89.6	1.756	"	20.7	124.5
5 Novo	10.5	.097	182.0	1.695	"	29.2	195.0
6 McInnes	36.6	.202	161.0	.892	"	100 0	132.0
7 Novo	17.4	.196	77.8	.875	"	100.0	132.0
8 Styrian	32.2	.165	154.0	.791	"	53.1	94.2
9 McInnes	31.9	.176	145.0	.798	"	36.9	94.2
10 Novo	7.0	.174	30.7	.758	"	100.0	94.2
11 Styrian	14.7	.149	63.2	.642	"	40.0	342.0
12 Novo	14.4	.148	67.6	.695	"	26.3	342.0
13 Novo	41.9	.273	189.0	1.230	"	28.6	175.2
14 Styrian	36.1	.284	165.0	1.300	"	42.8	175.2
15 Jessop	18.8	.398	86.2	1.820	"	9.6	124.5
16 Rex	23.6	.430	106.0	1.930	Tool failed	9.6	123.2
17 Styrian	34.9	.702	163.0	3.270	Time up	20.3	100.0
18 McInnes	11.3	.732	.....	.....	Tool failed	2.5	117.2
19 Novo	37.3	.774	167.0	3.480	Time up	13.0	106.6
20 Poldi	14.4	.834	61.9	3.570	Tool failed	0.0	117.2
21 A. & W	15.8	.902	64.9	3.710	"	3.8	117.2
22 Styrian	18.2	.207	42.0	.477	Time up	17.1	342.0
23 McInnes	12.4	.193	38.2	.593	"	17.5	342.0
24 Styrian	11.4	.195	26.8	.458	"	11.9	342.0
25 Rex	28.2	.452	61.5	.984	"	17.0	123.2
26 Styrian	75.0	.600	175.0	1.400	"	50.9	107.6
27 Novo	69.5	.582	170.0	1.420	"	32.4	90.4
28 McInnes	79.8	.614	191.0	1.470	"	27.4	116.4
29 Poldi	78.6	.614	184.0	1.440	"	34.7	122.7
30 A. & W	72.9	.595	169.9	1.380	"	23.0	108.0
31 Mushet	25.1	.591	60.3	1.420	"	100.	109.3

TABLE IV

Experiments with High-Speed Tool Steel on Cast Iron

Trials to Determine Variation of Durability with Cutting Speed

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended. Speed	Intended. Cut & Feed	Actual Speed	Actual Cut	Actual Feed	Area of Sec. of cut	Duration of Trial
			Ft./Min.	Ins.	Ft./Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Styrian	18	59	90	$\frac{1}{16}$x$\frac{3}{32}$	91.5	$\frac{1}{16}$	.0952	.00595	44
2 "	18	60	100	"	102.5	$\frac{1}{16}$	.0952	.00595	28½
3 "	18	61	110	"	110.6	$\frac{1}{16}$	.0952	.00595	43½
4 "	18	62	120	"	120.6	$\frac{1}{16}$	.0952	.00595	41⅓
5 Mushet	5	58	90	$\frac{1}{8}$x$\frac{1}{32}$	91.6	$\frac{1}{8}$	.0312	.00390	12¼
6 McInnes	5	54	95	"	95.3	$\frac{1}{8}$	.0312	.00390	62
7 "	5	55	100	"	100.3	$\frac{1}{8}$	.0312	.00390	61½
8 "	5	56	110	"	110.9	$\frac{1}{8}$	.0312	.00390	62⅓
9 "	5	57	120	"	123.4	$\frac{1}{8}$	.0312	.00390	31
10 Novo	4	50	85	$\frac{1}{8}$x$\frac{1}{16}$	86.1	$\frac{1}{8}$	.0642	.00800	29
11 "	4	51	95	"	98.7	$\frac{1}{8}$	.0642	.00800	27½
12 "	4	52	105	"	105.2	$\frac{1}{8}$	.0642	.00800	30
13 "	4	53	115	"	114.9	$\frac{1}{8}$	.0642	.00800	31½
14 Poldi	19	63	105	$\frac{3}{16}$x$\frac{1}{16}$	106.8	$\frac{3}{16}$	.0642	.01200	22½
15 "	19	64	115	"	116.1	$\frac{3}{16}$	.0642	.01200	21⅚
16 "	19	65	125	"	125.7	$\frac{3}{16}$	.0642	.01200	22
17 A. & W.	20	66	110	$\frac{1}{4}$x$\frac{1}{16}$	109.3	$\frac{1}{4}$	.0642	.01600	16½
18 "	20	67	120	"	120.0	$\frac{1}{4}$	.0642	.01600	18½
19 "	20	68	130	"	130.4	$\frac{1}{4}$	.0642	.01600	19¼

TABLE IV—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Styrian..........	31.9	.726	70.0	1.59	Time up	12.00	107.0
2 "	23.1	.812	48.2	1.69	Tool failed	7.76	107.0
3 "	38.1	.877	87.9	2.02	Time up	11.80	107.0
4 "	39.5	.956	96.6	2.34	"	5.50	107.0
5 Mushet..........	2.9	.238	12.1	.99	Tool failed	0.00	102.0
6 McInnes..........	15.3	.247	65.7	1.06	Time up	50.57	102.0
7 "	16.0	.261	71.3	1.16	"	25.60	102.0
8 "	17.9	.288	78.5	1.26	"	13.00	102.0
9 "	9.9	.321	43.7	1.41	Tool failed	6.37	102.0
10 Novo	13.3	.460	61.8	2.13	Time up	7.53	109.2
11 "	14.5	.527	66.0	2.40	"	5.63	109.2
12 "	16.9	.562	83.1	2.77	"	12.20	109.2
13 "	19.3	.614	88.8	2.82	"	3.31	109.2
14 Poldi	12.9	.572	85.7	3.81	"	13.90	117.2
15 "	13 5	.622	92.6	4.25	"	35.50	117.2
16 "	14.8	.672	102.0	4.64	"	100.00	117.2
17 A. & W..........	9.6	.584	87.1	5.28	"	13.40	113.9
18 "	11.9	.642	106.0	5.72	"	100.00	113.9
19 "	13.4	.697	118.0	6 16	"	15.70	113.9

TABLE V

Experiments with High-Speed Tool Steel on Cast Iron

Trials to Determine Variation of Durability with Hardness

1	2	3	4	5 & 6	7	8	9	10	11
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Intended		Actual	Actual		Area of sec. of cut	Duration of Trial
			Speed	Cut & Feed	speed	Cut	Feed		
			Ft. Min.	Ins.	Ft. Min.	Ins.	Ins.	Sq. Ins.	Min.
1 Novo...	22	94	50	$\frac{1}{8}\times\frac{1}{32}$	50.9	$\frac{1}{8}$	.0312	.00390	83
2 Poldi...	22	96	75	"	75.1	$\frac{1}{8}$	.0312	.00390	$88\frac{1}{2}$
3 Styrian.	23	85	75	"	75.2	$\frac{1}{8}$	.0312	.00390	$38\frac{1}{2}$
4 Novo...	15	91	100	"	100.3	$\frac{1}{8}$	.0312	.00390	$37\frac{3}{4}$
5 A. & W.	21	88	100	"	101.5	$\frac{1}{8}$	.0312	.00390	38
6 McInnes	17	70	100	"	101.9	$\frac{1}{8}$	.0312	.00390	$36\frac{3}{4}$
7 Poldi...	26	73	125	"	125.8	$\frac{1}{8}$	.0312	.00390	$30\frac{1}{2}$
8 A. & W.	16	79	130	"	130.0	$\frac{1}{8}$	.0312	.00390	$29\frac{5}{6}$
9 Styrian.	25	76	130	"	131.2	$\frac{1}{8}$	.0312	.00390	$29\frac{3}{4}$
10 Novo...	24	82	130	"	132.0	$\frac{1}{8}$	.0312	.00390	$29\frac{3}{4}$
11 Poldi...	22	95	50	$\frac{1}{8}\times\frac{1}{16}$	50.4	$\frac{1}{8}$	.0642	.00802	$33\frac{3}{4}$
12 A. & W.	23	86	70	"	70.9	$\frac{1}{8}$	.0642	.00802	$23\frac{5}{6}$
13 A. & W.	15	92	95	"	95.0	$\frac{1}{8}$	.0642	.00802	28
14 McInnes	21	89	95	"	95.2	$\frac{1}{8}$	.0642	.00802	$20\frac{1}{2}$
15 Styrian..	17	71	95	"	95.2	$\frac{1}{8}$	.0642	.00802	27
16 Poldi...	16	80	120	"	120.0	$\frac{1}{8}$	.0642	.00802	9
17 Novo...	25	77	120	"	121.2	$\frac{1}{8}$	.0642	.00802	21
18 McInnes	24	83	120	"	122.7	$\frac{1}{8}$	.0642	.00802	$21\frac{1}{2}$
19 A. & W.	26	74	140	"	143.4	$\frac{1}{8}$	.0642	.00802	$18\frac{1}{2}$
20 Novo..	23	87	65	$\frac{3}{16}\times\frac{1}{16}$	65.5	$\frac{3}{16}$	.0642	.01200	33
21 Styrian..	21	90	85	"	85.2	$\frac{3}{16}$	.0642	.01200	$32\frac{1}{6}$
22 Poldi...	15	93	85	"	86.2	$\frac{3}{16}$	.0642	.01200	$25\frac{3}{4}$
23 Novo...	17	72	85	"	88.8	$\frac{3}{16}$	.0642	.01200	24
24 McInnes	26	75	100	"	101.1	$\frac{3}{16}$	.0642	.01200	22
25 Styrian..	16	81	110	"	109.8	$\frac{3}{16}$	.0642	.01200	$13\frac{1}{4}$
26 A. & W.	24	84	110	"	110.6	$\frac{3}{16}$	.0642	.01200	16
27 Poldi...	25	78	110	"	111.5	$\frac{3}{16}$	.0642	.01200	21
28 Rex	32	127	70	"	72.2	$\frac{3}{16}$	.0642	.01200	29

TABLE V—(*Continued*)

1	12	13	14	15	16	17	18
Name of Brand of Tool Steel	Area Machined		Weight Removed		Cause of Withdrawal	Comparative Durability of Tool	Hardness of Test Piece
	Total	Per Min.	Total	Per Min.			
	Sq. Ft.	Sq. Ft.	Lbs.	Lbs.			
1 Novo	10.9	.132	55.4	.668	Time up	67.6	167.5
2 Poldi	17.2	.195	75.9	.858	"	68.1	167.5
3 Styrian	7.5	.195	35.8	.929	"	15.7	122.2
4 Novo	9.9	.262	45 2	1.200	"	100.0	132.0
5 A. & W.	10.0	.264	46.0	1.210	"	31.0	124.8
6 McInnes	9.6	.264	44.8	1.220	"	60.0	90.3
7 Poldi	9.9	.327	48.2	1.580	"	24.8	95.9
8 A. & W.	10.1	.338	44.1	1.480	"	12.2	109.8
9 Styrian	10.1	.341	45.7	1.540	"	100.0	102.4
10 Novo	10.2	.343	47.5	1.600	"	12.1	111.2
11 Poldi	9.0	.269	41.1	1.220	"	27.5	167.5
12 A. & W.	9.0	.379	41.2	1.730	"	38.8	122.2
13 A. & W.	44.2	.508	59.1	2.110	"	100.0	132.0
14 McInnes	10.4	.509	43.7	2.130	Tool failed	.0	124.8
15 Styrian	13.7	.509	58.9	2.180	Time up	100.0	90.3
16 Poldi	5.7	.642	24.1	2.680	Tool failed	.0	109.8
17 Novo	13.6	.649	61.7	2.940	Time up	100.0	102.4
18 McInnes	14.1	.657	65.6	3.050	"	35.0	111.2
19 A. & W.	14.2	.767	64.4	3.480	"	15.1	95.9
20 Novo	11.5	.350	79.2	2.400	"	65.5	122.2
21 Styrian	14.6	.455	98.7	3.070	"	13.1	124.8
22 Poldi	18.5	.461	73.5	2.860	"	10.4	132.0
23 Novo	11.4	.475	77.3	3.220	"	100 0	90.3
24 McInnes	11.9	.541	78.5	3.570	"	35.8	95.9
25 Styrian	7.7	.588	50.8	3.850	"	3.6	109.8
26 A. & W.	9.5	.592	64.3	4.020	"	26.0	111.2
27 Poldi	12.5	.597	82.1	3.910	"	100.0	102.4
28 Rex	11.2	.386	72.3	2.490	"	4.7	123.2

TABLE VI

Experiments with High-Speed Tool Steel on Cast Iron

Preliminary Trials

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel.	Test Piece No.	Trial No.	Total output of Motor	Required to drive lathe and countershaft	Net required for cutting	Actual cutting speed
					Col. (4) — (5)	Ft. Min.
1 Styrian.........	28	3	2.52	.65	1.87	54.8
2 "	"	4	2.78	.67	2.11	36.2
3 "	"	5	2.30	.63	1.67	32.5
4 "	"	6	3.05	.70	2.35	60.5
5 "	"	7	2.29	.63	1.66	59.6
6 "	"	8	1.29	.53	.76	58.0
7 "	"	9	3.08	.70	2.38	52.1
8 "	"	10	2.42	.64	1.78	47.6
9 "	"	11	1.46	.55	.91	41.2
10 McInnes........	1	23	1.83	.58	1.25	28.4
11 "	"	24	1.90	.59	1.31	31.8
12 "	"	25	1.87	.59	1.28	31.9
13 Novo..........	"	27	1.48	.55	.93	40.7
14 "	"	28	1.67	.57	1.10	43.7
15 "	"	29	1.41	.54	.87	42.5
16 Styrian	"	30	1.52	.55	.97	41.3
17 Novo..........	"	31	1.42	.54	.88	41.7
18 Styrian.........	27	130	3.06	.67	2.39	152.1
19 Novo..........	"	131	2.83	.55	2.28	153.1
20 McInnes........	"	132	......	...	....	150.0
21 Styrian.........	16	133	4.89	.89	4.00	111.0
22 Novo..........	"	134	3.12	.68	2.44	107.2
23 Styrian.........	23	135	2.74	.64	2.10	133.8
24 "	"	136	2.69	.63	2.06	134.3
25 "	"	137	2.45	.60	1.85	102.9
26 Novo..........	"	138	......	...	....	106.3
27 "	22	139	2.43	.60	1.83	101.5
28 Styrian.........	"	140	2.50	.65	1.85	79.5
29 Jessop..........	31	141	2.50	.65	1.85	53.3
30 "	"	142	2.82	.64	2.18	75.2
31 "	32	143	2.82	.64	2.18	85.0

TABLE VI—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting force on point of Tool. Total calculated	Cutting force on point of Tool. Per Sq. In. Area of cut	Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Lbs.	Lbs.	Ins.	Sq. In.	
1 Styrian.....	1126	129300	$\frac{3}{8} \times \frac{3}{128}$	.00870	114.5
2 "	1923	123200	$\frac{1}{2} \times \frac{1}{32}$	.01560	114.5
3 "	1696	106000	$\frac{1}{4} \times \frac{1}{16}$	.01600	114.5
4 "	1282	107800	$\frac{1}{8} \times \frac{3}{32}$	.01190	114.5
5 "	920	114800	$\frac{1}{8} \times \frac{1}{16}$	.00802	114.5
6 "	432	110800	$\frac{1}{8} \times \frac{1}{32}$	.00390	114.1
7 "	1508	130000	$\frac{3}{8} \times \frac{1}{32}$	.01160	114.5
8 "	1235	106500	$\frac{3}{8} \times \frac{1}{32}$	.01160	114.5
9 "	728	93400	$\frac{1}{4} \times \frac{1}{32}$	.00780	114.5
10 McInnes......	1451	181000	$\frac{1}{8} \times \frac{1}{16}$	.00802	342.0
11 "	1360	169800	"	.00802	342.0
12 "	1325	165300	"	.00802	342.0
13 Novo.........	754	188000	$\frac{1}{16} \times \frac{1}{16}$	.00401	342.0
14 "	832	207000	"	.00401	342.0
15 "	675	168200	"	.00401	342.0
16 Styrian.......	773	192500	"	.00401	342.0
17 Novo.........	697	173500	"	.00401	342.0
18 Styrian......	519	133000	$\frac{1}{8} \times \frac{1}{32}$	.00390	132.0
19 Novo.........	492	126000	"	.00390	132.0
20 McInnes......	....	.....	"	.00390	132.0
21 Styrian.......	1189	99100	$\frac{3}{16} \times \frac{1}{16}$	.01200	109.8
22 Novo.........	752	93800	$\frac{1}{8} \times \frac{1}{16}$	.00802	109.8
23 Styrian.......	518	132800	$\frac{1}{8} \times \frac{1}{32}$	.00390	122.2
24 "	507	130000	"	.00390	122.2
25 "	593	152000	"	.00390	122.2
26 Novo.........	....	......	"	.00390	122.2
27 "	595	152500	"	.00390	167.5
28 Styrian.......	768	196800	"	.00390	167.5
29 Jessop........	1145	142800	$\frac{1}{8} \times \frac{1}{16}$	.00802	124.5
30 "	958	119300	"	.00802	124.5
31 "	847	105600	"	.00802	124.5

TABLE VII

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

SKIN CUT TRIALS

1	2	3	4	5	6	7
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Horse-Power: Total Output of Motor	Horse-Power: Required to drive lathe and countershaft	Horse-Power: Net Required for Cutting	Actual Cutting Speed
					Col. (4) − (5)	Ft./Min.
1 Styrian	28	1	1.22	.52	0.70	45.2
2 Styrian	28	2	0.82	.49	0.33	36.3
3 McInnes	29	12	1.47	.55	0.92	46.2
4 McInnes	29	13	2.53	.65	1.88	59.5
5 McInnes	29	14	1.14	.52	0.62	36.4
6 Styrian	3	97	1.38	.54	0.84	50.6
7 Styrian	6 & 7	98	1.67	.57	1.10	55.2
8 Novo	8	99	1.48	.55	0.93	55.0
9 McInnes	9	100	1.74	.57	1.17	57.4
10 Novo	10	101	1.96	.60	1.36	55.5
11 McInnes	11	102	1.74	.57	1.17	54.4
12 Poldi	12 & 13	103	1.86	.59	1.27	55.6
13 A & W	14	104	1.38	.54	0.84	55.3
14 A & W	4	105	1.82	.58	1.24	56.0
15 Styrian	5	106	2.00	.60	1.40	67.9
16 Novo	18	107	2.12	.61	1.51	68.8
17 McInnes	19	108	2.29	.63	1.66	68.5
18 McInnes	19	109	2.29	.63	1.66	68.5
19 Poldi	20	110	2.50	.65	1.85	68.0
20 Novo	20	111	2.41	.64	1.77	68.2
21 Styrian	17	112	1.88	.59	1.29	75.3
22 Novo	26	113	1.88	.59	1.29	75.2
23 McInnes	25	114	1.78	.58	1.20	75.7
24 Poldi	16	115	1.83	.58	1.25	74.7
25 A & W	24	116	1.96	.60	1.36	73.9
26 Styrian	23	117	1.84	.58	1.26	72.2
27 Poldi	21	118	1.85	.58	1.27	75.0
28 A & W	15	119	2.19	.62	1.57	74.2
29 McInnes	22	120	2.02	.60	1.42	73.8
30 Styrian	22	121	1.76	.58	1.18	72.5
31 Jessop	32	122	2.00	.60	1.40	46.1

TABLE VII—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. In.	
1 Styrian	511	101000	$\frac{7}{32}$x$\frac{3}{128}$	.00507	114.5
2 Styrian	300	59300	"	.00507	114.5
3 McInnes......	658	168500	$\frac{1}{4}$x$\frac{1}{64}$	.00390	195.0
4 McInnes......	1042	133800	$\frac{1}{4}$x$\frac{1}{32}$	.00780	195.0
5 McInnes......	562	144000	$\frac{1}{4}$x$\frac{1}{64}$	.00390	195.0
6 Styrian	548	93800	$\frac{3}{16}$x$\frac{1}{32}$	.00585	94.2
7 Styrian.......	658	112500	"	.00585	107.6
8 Novo.........	558	95500	"	.00585	94.3
9 McInnes......	673	115000	"	.00585	138.6
10 Novo.........	809	138300	"	.00585	106.8
11 McInnes......	710	121300	"	.00585	109.3
12 Poldi	754	129000	"	.00585	103.3
13 A & W	502	85800	"	.00585	117.2
14 A & W	732	125000	"	.00585	109.2
15 Styrian.......	682	116300	"	00585	102.0
16 Novo.........	725	185800	$\frac{1}{8}$x$\frac{1}{32}$	.00390	107.0
17 McInnes......	800	205000	"	.00390	117.2
18 McInnes......	800	205000	"	.00390	117.2
19 Poldi.........	899	230000	"	.00390	113.9
20 Novo...	858	219600	"	.00390	113.9
21 Styrian.......	565	145000	"	.00390	90.3
22 Novo.........	567	145200	"	.00390	95.9
23 McInnes	524	134300	"	.00390	102.4
24 Poldi.........	553	141800	"	.00390	109.8
25 A & W	608	155800	"	00390	111.2
26 Styrian.	577	147800	"	.00390	122.2
27 Poldi.........	559	143200	"	.00390	124.8
28 A & W	699	179000	"	.00390	107.0
29 McInnes	636	163000	"	.00390	167.5
30 Styrian.	538	137800	"	.00390	167.5
31 Jessop	1001	128500	$\frac{1}{4}$x$\frac{1}{32}$	.00780	123.2

TABLE VIII

Experiments with High-Speed Tool Steel on Cast Iron

Endurance Trials

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Total Output of Motor	Required to drive lathe and countershaft	Net Required for Cutting	Actual Cutting Speed
					Col. (4) — (5)	Ft. Min.
1 Novo	29	15	2.83	.68	2.15	47.6
2 Styrian	30	17	2.52	.65	1.87	48.3
3 McInnes	30	18	2.31	.63	1.68	52.4
4 Jessop	31	124	3.10	.68	2.42	76.9
5 Novo	29	16	3.58	.75	2.83	37.6
6 McInnes	27	19	1.57	.56	1.01	77.8
7 Novo	27	20	1.49	.49	1.00	75.5
8 Styrian	3	36	1.34	.54	0.80	63.6
9 McInnes	3	37	1.33	.47	0.86	67.7
10 Novo	3	38	1.27	.47	0.80	67.1
11 Styrian	1	21	1.56	.56	1.00	28.0
12 Novo	1	22	1.66	.56	1.10	27.7
13 Novo	2	34	2.13	.61	1.52	51.1
14 Styrian	2	35	1.78	.58	1.20	53.2
15 Jessop	31	123	2.98	.66	2.32	74.5
16 Rex	32	126	3.05	.67	2.38	80.4
17 Styrian	12	45	3.16	.68	2.48	88.7
18 McInnes	14	47	3.53	.73	2.80	92.4
19 Novo	13	46	3.67	.74	2.93	97.7
20 Poldi	14	48	4.49	.83	3.66	105.2
21 A. & W	14	49	4.83	.87	3.96	113.6
22 Styrian	1	26	1.19	.52	0.67	38.7
23 McInnes	1	32	1.24	.53	0.71	36.1
24 Styrian	1	33	1.29	.47	0.82	36.6
25 Rex	32	125	2.03	.57	1.46	84.5
26 Styrian	6 & 7	39	1.89	.57	1.32	76.6
27 Novo	7 & 8	40	1.56	.50	1.06	74.3
28 McInnes	8 & 9	41	1.92	.59	1.33	77.5
29 Poldi	9 & 10	42	2.04	.60	1.44	77.4
30 A. & W.	10 & 11	43	1.96	.54	1.42	75.0
31 Mushet	11	44	1.79	.53	1.26	74.6

TABLE VIII—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. Ins.	
1 Novo	1492	191500	$\frac{1}{2} \times \frac{1}{64}$	.00780	195.0
2 Styrian	1275	163500	"	.00780	124.2
3 McInnes	1059	135800	"	.00780	124.2
4 Jessop	1040	133300	$\frac{1}{4} \times \frac{1}{32}$	.00780	124.5
5 Novo	2482	159100	$\frac{1}{2} \times \frac{1}{32}$	.01560	195.0
6 McInnes	428	109700	$\frac{1}{8} \times \frac{1}{32}$	.00390	132.0
7 Novo	437	112000	"	.00390	132.0
8 Styrian	415	106400	"	.00390	94.2
9 McInnes	419	107300	"	.00390	94.2
10 Novo	394	101000	"	.00390	94.2
11 Styrian	1179	147000	$\frac{1}{8} \times \frac{1}{16}$	.00802	342.0
12 Novo	1310	163500	"	.00802	342.0
13 Novo	982	122500	"	.00802	175.2
14 Styrian	745	93000	"	.00802	175.2
15 Jessop	1029	128300	"	.00802	124.5
16 Rex	978	122000	"	.00802	123.2
17 Styrian	924	77900	$\frac{1}{8} \times \frac{3}{32}$	.01190	100.0
18 McInnes	1000	84000	"	.01190	117.2
19 Novo	1010	84900	"	.01190	106.6
20 Poldi	1148	96500	"	.01190	117.2
21 A. & W.	1151	96800	"	.01190	117.2
22 Styrian	571	142300	$\frac{1}{16} \times \frac{1}{16}$	.00401	342.0
23 McInnes	649	161600	"	.00401	342.0
24 Styrian	739	184000	"	.00401	342.0
25 Rex	570	142000	"	.00401	123.2
26 Styrian	569	95700	$\frac{1}{16} \times \frac{3}{32}$	.00595	107.6
27 Novo	471	79200	"	.00595	90.4
28 McInnes	567	95300	"	.00595	116.4
29 Poldi	615	103200	"	.00595	122.7
30 A. & W.	625	105000	"	.00595	108.0
31 Mushet	557	93800	"	.00595	109.3

TABLE IX

Experiments with High-Speed Tool Steel on Cast Iron

Trials to Determine Variation of Durability with Cutting Speed

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel	Test Piece No.	Trial No.	Total Output of Motor	Required to drive lathe and countershaft	Net Required for Cutting	Actual Cutting Speed
					Col. (4)—(5)	Ft./Min.
1 Styrian.........	18	59	2.38	.59	1.79	91.5
2 Styrian.........	18	60	2.71	.63	2.08	102.5
3 Styrian.........	18	61	2.84	.65	2.19	110.6
4 Styrian........	18	62	3.08	.67	2.41	120.6
5 Mushet.........	5	58	1.77	.52	1.25	91.6
6 McInnes........	5	54	1.58	.50	1.08	95.3
7 McInnes........	5	55	1.78	.52	1.26	100.3
8 McInnes........	5	56	2.16	.59	1.57	110.9
9 McInnes........	5	57	2.19	.57	1.62	123.4
10 Novo...........	4	50	2.61	.62	1.99	86.1
11 Novo...........	4	51	2.92	.66	2.26	98.7
12 Novo...........	4	52	3.14	.68	2.46	105.2
13 Novo...........	4	53	3.76	.75	3.01	114.9
14 Poldi...........	19	63	4.48	.83	3.65	106.8
15 Poldi...........	19	64	5.06	.90	4.16	116.1
16 Poldi...........	19	65	5.20	.92	4.28	125.7
17 A. & W.........	20	66	6.50	1.07	5.43	109.3
18 A. & W.........	20	67	5.98	1.01	4.97	120.0
19 A. & W.........	20	68	6.04	1.01	5.03	130.4

TABLE IX—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool: Total Calculated	Cutting Force on Point of Tool: Per Sq. In. Area of Cut	Size of Cut	Area of Cut (cut × feed)	Hardness of Test Piece
	Lbs.	Lbs.	Ins.	Sq. Ins.	
1 Styrian.......	647	108800	$\frac{1}{16} \times \frac{3}{32}$	.00595	107.0
2 Styrian.......	670	112600	"	.00595	107.0
3 Styrian.......	653	109800	"	.00595	107.0
4 Styrian.......	661	111000	"	.00595	107.0
5 Mushet.......	450	115400	$\frac{1}{8} \times \frac{1}{32}$	.00390	102.0
6 McInnes	374	96000	"	.00390	102.0
7 McInnes......	414	106100	"	.00390	102.0
8 McInnes......	468	120000	"	.00390	102.0
9 McInnes......	433	111100	"	.00390	102.0
10 Novo.........	763	95300	$\frac{1}{8} \times \frac{1}{16}$	.00802	109.2
11 Novo.........	757	94400	"	.00802	109.2
12 Novo.........	772	96300	"	.00802	109.2
13 Novo.........	866	108000	"	.00802	109.2
14 Poldi.........	1128	94000	$\frac{3}{16} \times \frac{1}{16}$	.01200	117.2
15 Poldi.........	1182	98500	"	.01200	117.2
16 Poldi.........	1124	93750	"	.01200	117.2
17 A. & W.......	1640	102500	$\frac{1}{4} \times \frac{1}{16}$	.01600	113.9
18 A. & W.......	1366	85500	"	.01600	113.9
19 A. & W......	1273	79600	"	.01600	113.9

TABLE X

EXPERIMENTS WITH HIGH-SPEED TOOL STEEL ON CAST IRON

TRIALS TO DETERMINE VARIATION OF DURABILITY WITH HARDNESS

1	2	3	4	5	6	7
			Horse-Power			
Name of Brand of Tool Steel.	Test Piece No.	Trial No.	Total output of Motor	Required to drive lathe and countershaft	Net required for cutting	Actual cutting speed
					Col. (4) — (5)	Ft./Min.
1 Novo	22	94	1.57	.56	1.01	50.9
2 Poldi	22	96	2.03	.55	1.48	75.1
3 Styrian	23	85	2.08	.56	1.52	75.2
4 Novo	15	91	1.88	.54	1.34	100.3
5 A. & W.	21	88	2.18	.57	1.61	101.5
6 McInnes	17	70	1.87	.53	1.34	101.9
7 Poldi	26	73	2.51	.61	1.90	125.8
8 A. & W.	16	79	2.38	.59	1.79	130.0
9 Styrian	25	76	2.26	.58	1.68	131.2
10 Novo	24	82	2.54	.61	1.93	132.0
11 Poldi	22	95	2.44	.64	1.80	50.4
12 A. & W.	23	86	2.73	.63	2.10	70.9
13 A. & W.	15	92	2.62	.62	2.00	95.0
14 McInnes	21	89	4.07	.80	3.27	95.2
15 Styrian	17	71	2.65	.62	2.03	95.2
16 Poldi	16	80	3.88	.77	3.11	120.0
17 Novo	25	77	3.33	.70	2.63	121.2
18 McInnes	24	83	3.27	.70	2.57	122.7
19 A. & W.	26	74	3.83	.76	3.07	143.4
20 Novo	23	87	3.55	.75	2.80	65.5
21 Styrian	21	90	4.05	.79	3.26	85.2
22 Poldi	15	93	3.96	.78	3.18	86.2
23 Novo	17	72	3.36	.70	2.66	88.8
24 McInnes	26	75	3.68	.74	2.94	101.1
25 Styrian	16	81	4.58	.84	3.74	109.8
26 A. & W.	24	84	4.02	.78	3.24	110.6
27 Poldi	25	78	4.22	.80	3.42	111.5
28 Rex	32	127	3.50	.72	2.78	72.2

TABLE X—(*Continued*)

1	8	9	10	11	12
Name of Brand of Tool Steel	Cutting Force on Point of Tool		Size of Cut	Area of Cut (cut×feed)	Hardness of Test Piece
	Total Calculated	Per Sq. In. Area of Cut			
	Lbs.	Lbs.	Ins.	Sq. Ins.	
1 Novo.........	655	168000	$\frac{1}{8} \times \frac{1}{32}$	.00390	167.5
2 Poldi.........	650	166500	"	.00390	167.5
3 Styrian.......	668	171100	"	.00390	122.2
4 Novo.........	441	113100	"	.00390	132.0
5 A. & W.......	523	134200	"	.00390	124.8
6 McInnes......	434	111200	"	.00390	90.3
7 Poldi	498	127700	"	.00390	95.9
8 A. & W.......	454	116300	"	.00390	109.8
9 Styrian.......	422	108100	"	.00390	102.4
10 Novo.........	482	123500	"	.00390	111.2
11 Poldi.........	1179	147100	$\frac{1}{8} \times \frac{1}{16}$	.00802	167.5
12 A. & W.......	978	122000	"	.00802	122.2
13 A. & W.	695	86700	"	.00802	132.0
14 McInnes......	1134	141500	"	.00802	124.8
15 Styrian.......	704	87800	"	.00802	90.3
16 Poldi..	855	106500	"	.00802	109.8
17 Novo.........	717	89500	"	.00802	102.4
18 McInnes......	692	86300	"	.00802	111.2
19 A. & W.	706	88100	"	.00802	95.9
20 Novo.........	1410	117500	$\frac{3}{16} \times \frac{1}{16}$	.01200	122.2
21 Styrian.......	1264	105300	"	.01200	124.8
22 Poldi.........	1219	101500	"	.01200	132.0
23 Novo.........	989	82400	"	.01200	90.3
24 McInnes......	958	79800	"	.01200	95.9
25 Styrian.......	1123	93700	"	.01200	109.8
26 A. & W.......	967	80600	"	.01200	111.2
27 Poldi.........	1012	84500	"	.01200	102.4
28 Rex..........	1271	106000	"	.01200	123.2

V. Summary of Results

(a) *Variation of Cutting Force with Area of Cut*

The effort exerted by the tool in cutting was determined as explained in Part III (c). The horse-power lost in driving the lathe and countershaft was deducted from the total horse-power used during the trial, the difference being the net horse-power required for cutting. This was reduced to foot-pounds per minute, and divided by the cutting speed, giving the force exerted. The figures so obtained were reduced to pounds per unit area of cut, and plotted as ordinates upon a base of area of cut in Fig. 14. The curves show that the cutting force was not directly proportional to the area of cut, but decreased as the area increased, and that the average cutting force varied from 50 tons per square inch for soft cast iron to 85 tons per square inch for hard cast iron. Each curve shown in the figure represents a different hardness of cast iron. The relative hardness is shown in the table on the figure.

(b) *Variation of Durability of Tool with Cutting Speed*

In Fig. 15 are shown the curves which represent the relation between the durability of the tool and the cutting speed. These are important curves. Each curve represents a different hardness of cast iron. Referring to the middle curve, which is for cast iron of medium hardness, it will be seen that a cutting speed of 50 feet per minute is satisfactory, the durability being 100. If the speed is increased very materially, the durability decreases quite rapidly. It is evident that for each hardness of cast iron, the cutting speed allowable for a maximum durability exists where the vertical line indicating cutting speed is tangent to curves similar to those drawn.

(c) *Variation of Cutting Speed with the Hardness of Cast Iron*

The curve shown in Fig. 16 represents the advisable cutting speed on cast iron of varying hardness. This curve represents the result of all the tests of the different steels tested. This curve shows: (a) that any of the steels tested can remove very hard cast iron at a rate of 25 feet per minute; (b) that all of the steels tested begin to wear rapidly at speeds a little above 125 feet per minute. Between these two points the relation between a safe cutting speed and the hardness of the cast iron seems to be defi-

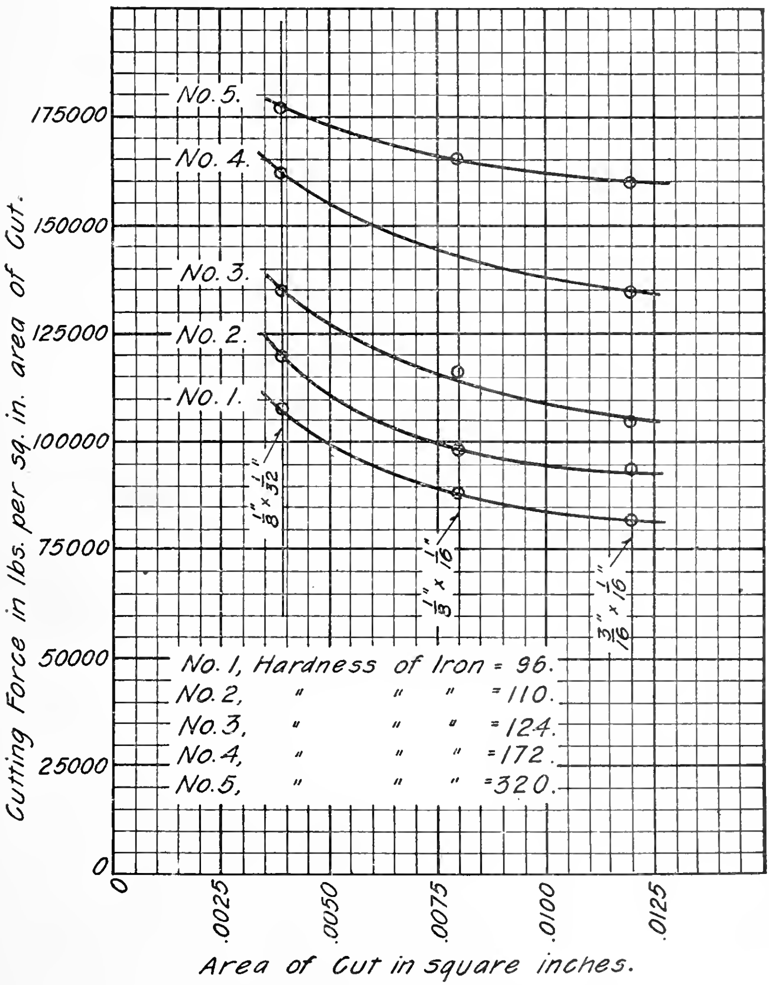


FIG. 14. CURVES SHOWING RELATION BETWEEN CUTTING FORCE ON POINT OF TOOL AND AREA OF CUT FOR CAST IRON OF VARYING HARDNESS

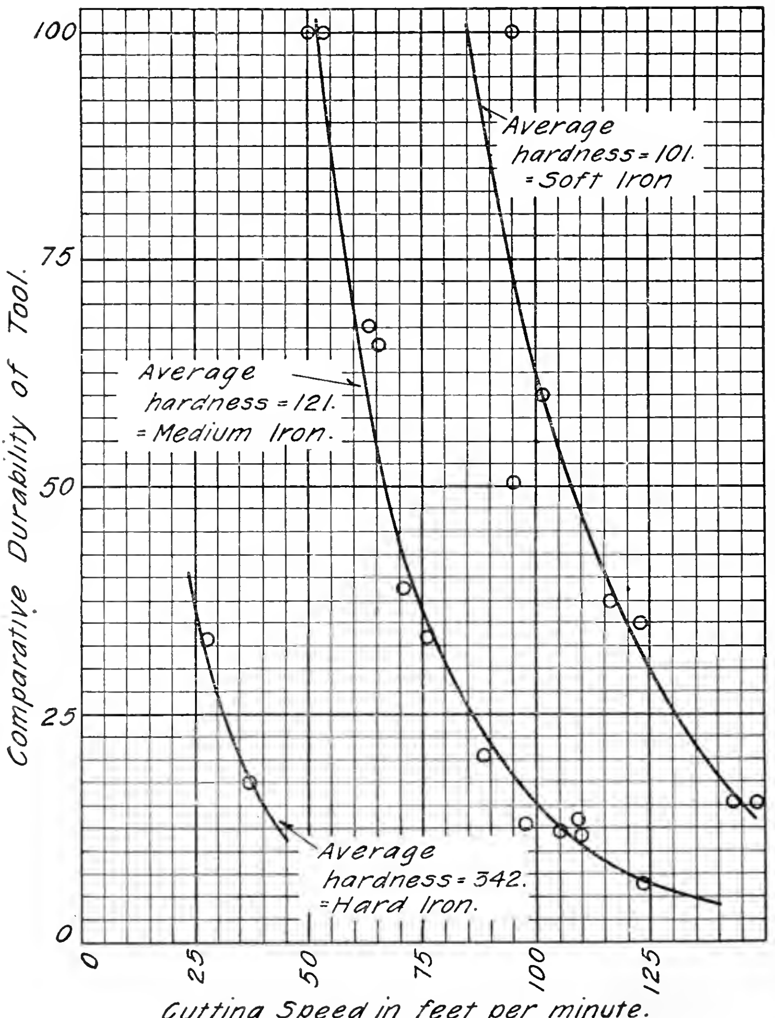


FIG. 15. CURVES SHOWING VARIATION OF DURABILITY OF TOOL WITH CUTTING SPEED FOR CAST IRON OF VARYING HARDNESS—AVERAGE OF ALL TOOL STEELS

nitely expressed by the curve. It would seem that cast iron of medium hardness, 100 to 120, could be cut at 125 feet per minute just as readily as at 70 feet per minute, as far as any injury to the tool is concerned. It must be remembered that this curve does not take into account the effect, on the cutting speed, of the variation in the area of cut; the experiments from which the

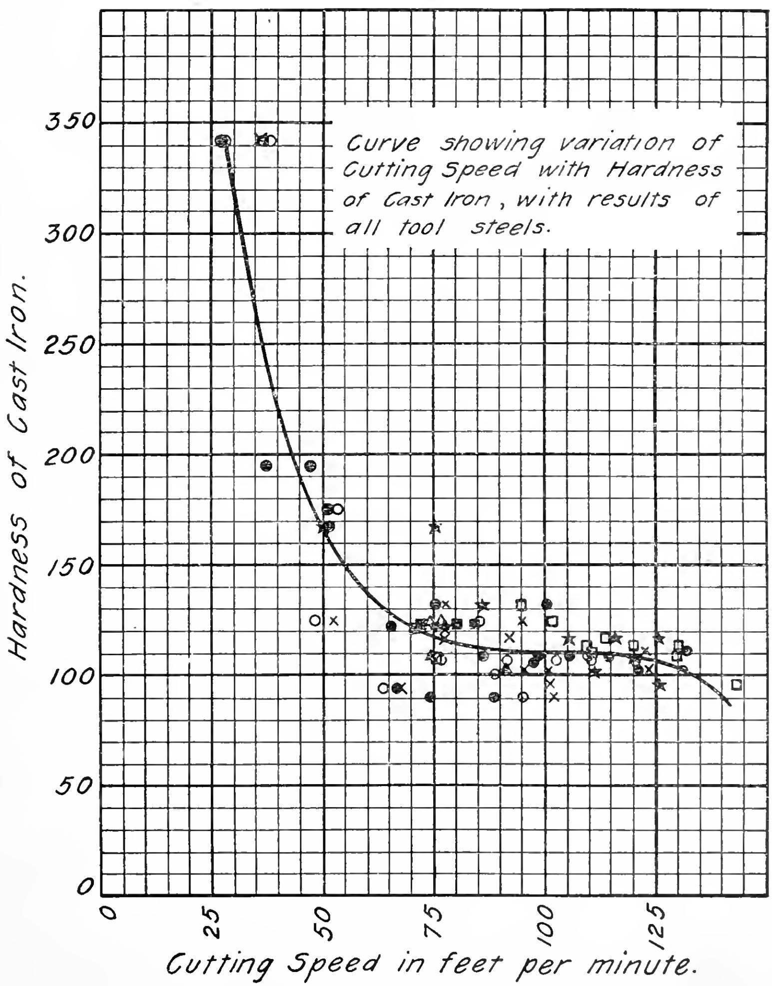


FIG. 16. CURVE SHOWING CUTTING SPEEDS IT IS ADVISABLE TO USE WITH A VARIATION IN THE HARDNESS OF CAST IRON

curve was plotted were in all cases those in which the cut was very nearly $\frac{1}{8}$ in. depth of cut by $\frac{1}{16}$ in. feed, so that there is but a slight variation in the area of cut in all of the experiments. From the curve of Fig. 16, we find the cutting speeds given in Table 4 to be applicable to the grades of iron manufactured by the different companies sending test pieces. In order that any company may make use of the curve shown in this figure, it will be necessary simply to determine the average hardness of its cast iron, as explained elsewhere, and where the horizontal line representing this hardness cuts the curve, the possible safe cutting speed may be read on the scale below. This curve should prove useful to various manufacturers.

TABLE 4

ALLOWABLE CUTTING SPEEDS FOR GRADES OF CAST IRON USED IN THE TESTS

Name of Company Sending Test Pieces		Average Hardness of Test Pieces	Allowable Cutting Speed
American Radiator Co., Chicago, Ill.	Pierce Plant	101.8	132.0
	Michigan Plant	110.7	118.0
	Detroit Plant	109.3	120.0
	——— Plant Marked 5-17-05	112.7	90.0
	——— Plant Marked B 5-26-05	138.1	60.0
	——— Plant Marked B 6-2-05	103.1	132.0
Crane Company, Chicago, Ill.	Grey Iron	132.0	63.0
	Ferro-Steel	342.0	28.0
Root, Van Dervoort Eng'g Co., East Moline, Ill.		175.2	48.0
University of Illinois, M. E. Dept. Shops.		136.3	60.0

(*d*) Generally speaking, all the steels tested proved equally effective. It is very evident that there are great possibilities ahead for high-speed steels. Before realizing their full benefit, however, certain advances must be made. Heavier machine tools must be built. The capacity of the motors and power plants

must be increased. Special hardening furnaces with temperature measuring devices must be available. More must be known concerning the chemical and physical properties of the various steels. (*e*) Tool steels are now available that will cut cast iron from two to three times as fast as was possible a few years ago. When every advantage has been taken of these possibilities, the cost of manufacturing many articles should be materially reduced.

VI. Reference List of Articles on High-Speed Steels

Experiments with a New Tool Steel: by F. Heissig, in *Stahl and Eisen*, January 1, 1901.

Results of tests made by Böhler Bros. and Co., Vienna and Berlin, on their Styrian Steel marked Böhler Rapid.

Extract of Report of Experiments of Taylor and White, at the Bethlehem Steel Co., S. Bethlehem, Pa.: in *Zeitschrift des Vereines Deutscher Ingenieure*, March 30, 1901.

The Taylor-White Process of Treating Tool Steel and Its Influence on the Mechanic Arts: by Charles Day, in *Journal of the Franklin Institute*, September, 1901.

High-Speed Steel: in *Zeitschrift des Vereines Deutscher Ingenieure*, September 28, 1901.

Report of experiments instituted by the Berlin section of the Vereines Deutscher Ingenieure. Test made on forged and cast steel and cast iron.

High-Speed Tool Steel: by F. Reiser, in *Stahl and Eisen*, January 15, 1903.

A discussion of the chemical properties of high-speed and self-hardening tool steels.

Speeds, Feeds and Angles of Metal-Cutting Tools: by F. Donaldson, in *American Machinist*, March 5, 1903.

Discussion of the relation of cutting angles to angles to which tools are ground.

The Requirements of Machine Tool Operation with Special Reference to the Motor Drive: by Charles Day, in *American Machinist*, Part 1, March 12, 1903, Part II, March 19, 1903.

Discussion of tools driven by electricity.

Metal Cutting with the New Tool Steels: by Oberlin Smith, in *Engineering Magazine*, April, 1903, Vol. 25.

Discussion of changes in the design and operation of machines to be wrought by the new tool steels.

Notes on High-Speed Tool Steels: by Henry H. Suplee, in *Engineering*, (London), July 31, 1903, Vol. 76.

Results of tests made at the Union Pacific Shops, Omaha, Nebraska.

Rapid Tool Steels: in *Engineering* (London), August 21, 1903, Vol. 76.

Chemical properties of the new steels with attainable speeds. Editorial.

Rapid-Cutting Tool Steels: in *Engineering* (London) October 30, 1903, Vol. 76.

Report on experiments made at the Manchester Municipal School of Technology under the direction of a joint committee from the above school and the Manchester Association of Engineers. A very elaborate and interesting report by Professor J. T. Nicolson, also reported in the American Machinist, November 19 and 26, 1903.

The Analysis of High-Speed Steels: in *Engineering* (London), November 20, 1903, Vol. 76.

Methods of testing for different chemical constituents

Cutting Speeds and Feeds with New Tool Steels: by Oberlin Smith, in *Engineering Magazine*, January, 1904, Vol. 26.

Record of actual results obtained.

Rapid-Cutting Steel: by Professor J. T. Nicolson, in *Technics*, January, 1904.

A very interesting summary of Berlin and Manchester experiments. The following formula is deduced:

$$V = \frac{K}{a + L} + M$$

V = allowable cutting speed in feet per minute

a = area of cut in square inches

K, L, M = constants for different materials

See Table 5. The chemical analyses to which these tables apply are given in Table 6. It is probable that these results were obtained under the most favorable conditions

and therefore represent the maximum results obtainable at the time of these experiments. It is a question whether these results can be attained in the work shop, where the conditions are frequently not so favorable.

TABLE 5

CONSTANTS FOR USE IN THE EQUATION GIVING THE RELATION BETWEEN CUTTING SPEED AND AREA OF CUT

(Experiments by Nicolson)

Constant	Fluid Pressed Steel			Cast-Iron Bars		
	Soft	Medium	Hard	Soft	Medium	Hard
K	1.950	1.850	1.030	3.100	1.650	1.300
L	.011	.016	0.160	.025	.030	.035
M	15.000	6.000	4.000	8.000	7.000	5.500

TABLE 6

CHEMICAL COMPOSITION OF MATERIALS REFERRED TO IN TABLE 5

(Experiments by Nicolson)

	Fluid Pressed Steel			Cast-Iron		
	Soft	Medium	Hard	Soft	Medium	Hard
Carbon	.198	.275	.514	.....	....	.....
Combined Carbon	.....	....	......	.459	.585	1.1500
Graphite	.....	....	......	2.603	2.720	1.8750
Silicon	.055	.086	.111	3.010	1.703	1.7890
Manganese	.605	.650	.792	1.180	.588	.3480
Sulphur	.026	.037	.033	.031	.061	.1614
Phosphorus	.035	.043	.037	.773	.526	.7320

The Heat Treatment of Steel: in *Proceedings of the Institute of Mechanical Engineers*, January, 1904, Sixth Report of the Alloys Research Committee.

Discussion of hardening, annealing and chemical properties of steel.

The Introduction of High-Speed Steels in Engineering Work Shops: in *Engineering* (London), March 4, 1904, Vol. 77.

High-Speed Tool Steel: Its Manufacture and Use: by J. M. Gledhill, in *Technics*, Part I, June, 1904; Part II, July, 1904.
Some constituents and processes used in the manufacture of high-speed steel.

Experiments with a Lathe-Tool Dynamometer: by Professor J. T. Nicolson, in *Trans. A. S. M. E.*, Vol. 25, 1904.
Measures all forces acting on a lathe tool while cutting. Valuable for designers of lathes. Discussion of influence of cutting angles on power required to cut.

A Twist Drill Dynamometer: by Wm. W. Bird and Howard O. Fairfield, in *Trans. A. S. M. E.*, Vol. 26, 1904.
Measures both the twist and torque of drill while cutting with high-speed drills.

The Chemical Analysis of High-Speed Steels and Alloys: by Fred Ibbotson, in *Technics*, October, 1904.

The Development and Use of High-Speed Tool Steel: by J. M. Gledhill, in *American Machinist*, December 22, 1904.
Interesting results of experiments made to find the effect of various chemical constituents on the cutting powers of the tool steel.

Feeds and Speeds for Lathe Work: by T. A. Sperry, in *American Machinist*, May 25, 1905.
Results of observations at the shops of the Cincinnati Milling Machine Company.

High-Speed Steel in the Factory: by O. M. Becker and Walter Brown, in *Engineering Magazine*, beginning September, 1905.
Conclusions of a practical study of the use of high-speed steel and its introduction into the factory.

Economy of High-Speed Steel Tools: by F. D. Smith and H. S. Greene. Thesis for a degree in Electrical Engineering in the College of Engineering, University of Illinois, June, 1905.
Tests made at the Chicago and Eastern Illinois Railway Shops, Danville, Illinois, showing that the cost of removing a pound of metal with low-speed steel is from 2.2 to 4.8 times as great as when using high-speed steel.

APPENDIX

Instructions for Hardening the Steels Used furnished by the makers.

(1) Directions for working Styrian Steel, marked Böhler Rapid

For Forging:

Heat to a bright red. Do not allow the heat to run as low as a cherry-red while forging. After forging allow the tool to cool slowly before hardening.

For Hardening: Lathe, Planer and Boring Tools.

Heat to a white heat but not to a scaling or melting point, just a good white heat. Cool in the air or a cold blast.

Houghton and Richards,
American Agents.

(2) Directions for working Jessop's "Ark" High-Speed Steel

For Forging:

Heat the steel to a canary color, retaining this heat until the tool is forged as nearly as possible to the shape required. The tool may be rough finished by grinding while yet hot on a dry emery wheel. It should then be laid aside in a dry place until black.

For Hardening:

Place the nose of the tool in a clear fire. Slowly heat the steel to a white or welding heat, not over one inch from the end. The nose of the tool should be made fusing hot. Then it should be placed under a strong, cold, dry air blast until cold.

William Jessop and Sons, Limited,
New York.

(3) Directions for working McInnes's "Extra" High-Speed Air-Hard Steel

For Forging and Hardening:

Forge the steel at the ordinary tool-steel forging heat; after the tool is forged to the desired shape, reheat the cutting end to a light cherry-red, and cool in an air blast. In order to bring out the quality of this steel when the tool is forged to the above instructions, it should be run at high speed in the lathe or planer until the edge is worn off two or three times and reground. After each grinding the tool gets better until it gets to its limit.

McInnes's Steel Company, Limited,
Corry, Pennsylvania.

(4) Directions for working Mushet "Special" High-Speed Steel

For Hardening:

When forged, the cutting end of the tool should be reheated to a white heat, and then immediately blown cold. While hot this steel must be kept from water.

(5) Directions for working "Air Novo" High-Speed Tool Steel

For Forging:

The steel must be heated thoroughly, so that it is hot all the way through. The forging color must be a very light yellow. Do not hammer the steel when it gets down to a dark red, but reheat it. After the tools are forged lay them down to cool.

For Hardening:

Heat the cutting edge only of the tool to a white welding heat. Heat it until it begins to flow. Then put the tool into a compressed air blast, or dip immediately into thin lard, linseed or fish oil until thoroughly cold.

Hermann Boker & Co.,
New York.

(6) Directions for working "Rex" High-Speed Tool Steel

For Forging:

Use a clean fire and forge at a bright red heat, holding the steel at this heat as nearly as possible while the forging is being done. Forging at too low a heat will cause the steel to burst in forging. When tool is forged lay it down in a dry place to cool.

For Hardening:

Use a clean fire or furnace and bring the point or cutting portion of the tool gradually to a sweating white heat. This heat is indicated by a flux, having the appearance of melted borax, forming on the nose of the tool. Confine the high heat as much as possible to the cutting portion of the tool. When the proper heat is reached, take from the fire and carefully remove the oxide scale which instantly forms on the heated portion of the tool. This can be done with a coarse file, and will permit the cutting portion of the tool to cool off much more uniformly and rapidly than if the oxide scale is allowed to remain. When extremely hard and tough metal is to be machined, blow cold in fan or dry compressed air blast.

Crucible Steel Company of America,
Pittsburg, Pa.

The directions received from the American Radiator Company for hardening the two foreign steels, "A & W" and "Poldi", applied to nipple dies. The same, however, were used in the tests for lathe tools, with the exception of being heated in a forge fire. They are as follows:

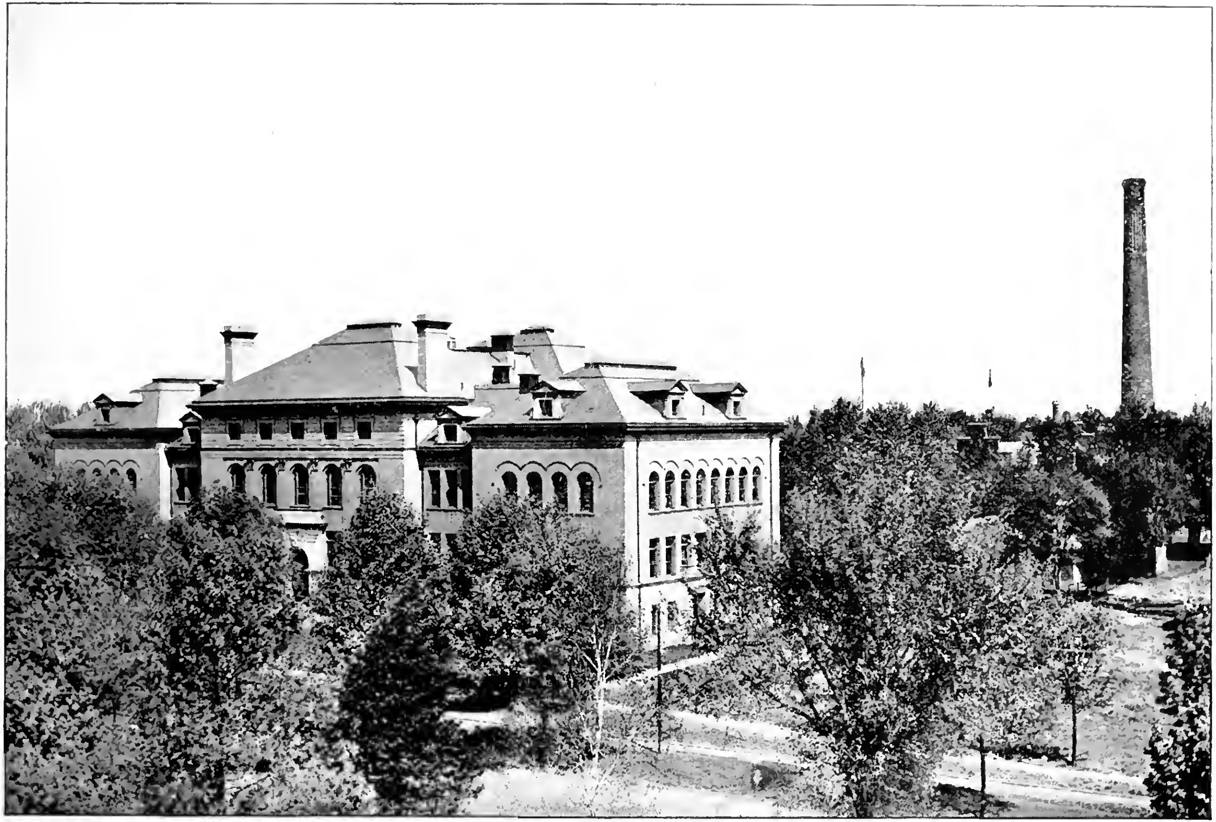
(7) For Hardening "A & W" High-Speed Tool Steels, manufactured by Armstrong, Whitworth and Company, Limited, England:

"When tempering the steel for nipple dies, we placed the dies in a retort, and heated them so

that the cutting end reached a white heat; then the dies were placed in a strong air blast and cooled to a cherry-red color, after which they were dropped into a tempering oil. Tempering in this manner gives by far the best wearing point to the steel".

(8) Directions for Hardening "Poldi" High-Speed Tool Steel:

"This steel was treated in a slightly different manner from the 'A & W'. The dies were heated to a white heat in a retort, and then cooled in an air blast until they were absolutely cold "



Engineering Building
Built in 1894

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 3 MARCH 1906

THE ENGINEERING EXPERIMENT STATION OF THE UNIVERSITY OF ILLINOIS

BY L. P. BRECKENRIDGE, DIRECTOR OF THE ENGINEERING EXPERIMENT STATION.

The Engineering Experiment Station of the University of Illinois was established by action of the Board of Trustees, December 8, 1903. It is the purpose of the station to carry on investigations along various lines of engineering, and to make studies of problems of importance to professional engineers, and to the manufacturing, mining, railway, constructional and industrial interests of the state. It is believed that this experimental work will result in contributions of value to engineering science and to the industries of the state, and that the pursuit of such investigations will give inspiration to students and add to the value of the instructional work in the College of Engineering.

The value to the state of the work done by the Agricultural Experiment Station has suggested the possibility of doing work of similar value to the industrial interests of the state. It is believed that Illinois is the first state to establish an engineering experiment station, but there is every reason to believe that many other states will soon move in such a direction. When a number of states have established such stations, it is entirely reasonable to suppose that the federal government may be depended upon to give the same aid to these engineering stations that it now does to the agricultural experiment stations.

II. Plan of Organization

The organization for directing and guiding the operations of the station consists of a director and a station staff. The staff consists of seven members, representing with the director the heads of the different departments of the College of Engineering. A corps of assistants will be appointed whose entire time will be devoted to the prosecution of such experimental investigations as may be approved by the station staff. Several assistants have already been appointed who have been detailed to take up special investigations under the supervision of some member of the staff. Preparations are being made for other experimental work, and as fast as the necessary apparatus and equipment can be arranged, additional assistants will be put in charge of the work. Encouragement and aid will be given to instructors already employed by the University who desire to take up some line of research work. Whenever such men prove to be successful experimenters and clear writers, some arrangement may be made whereby a part of their time may be devoted to the work of the station and a correspondingly proportionate part of their salary paid from the funds of the station.

III. Work Already Accomplished

The first work undertaken by the Engineering Experiment Station was an investigation of reinforced concrete and the properties of concrete affecting reinforced concrete construction. The results of this work are recorded in *Bulletin No. 1, Tests of Reinforced Concrete Beams, by Arthur N. Talbot*, which was published as University of Illinois Bulletin, Volume II, No. 1. September 1, 1904. This was one of the first extensive and systematic investigations on reinforced concrete made in this country, and the results aided in clearing up a number of controverted points. While the investigation was carried on largely as senior thesis work, the character of the work and the supervision and planning given to it, together with the method of furnishing materials and apparatus, warrant giving more weight to the results than may usually be given to results of student work. The investigation covered a considerable range. The results on bond between concrete and steel (plain and deformed bars) and on the relation between compressive stress and deformation were of interest. The measured deformations obtained in plain concrete beams showed

that up to the breaking point in tension the modulus of elasticity for tension is practically equal to that for compression, instead of being one-half as great, as had generally been assumed by writers on this subject. In reinforced concrete beams, the action of the steel and concrete during flexure was studied. It was shown that the concrete failed in tension at its usual breaking limit instead of carrying stress to ten times that limit, as had been claimed by some experimenters, and the added stretch in the steel at this point was clearly shown on the diagrams.

Among the results brought out by this investigation were the following: the stages of action during flexure; the accurate determination of the position of the neutral axis; a basis of calculation of resisting moment of beam based upon tension in the steel; the value of an experimental determination of the position of the neutral axis and of the percentage of steel suitable for a given concrete; the effect of elastic limit of steel and of form of bar upon strength of beam. The tests also opened up the field for further experimentation. The publication of the results was received with much interest by the engineering press and the engineering profession. The comments made gave testimony to the thoroughness of the work and to the great interest and value attached to the investigation, as throwing new light on a subject very much in need of scientific data. Requests for Bulletin No. 1 have come from all parts of the world. The investigation of reinforced concrete beams is being continued and experiments on reinforced concrete columns have been started.

Circular No. 1, High-Speed Tool Steels, by L. P. Breckenridge, was issued April 15, 1905. In this circular is given a brief review of the results of experiments made by different engineers with this new tool steel. Experiments with high-speed tool steels on cast iron have been in progress at the shops of the mechanical engineering department of the University during the last year. These tests have been carried on by H. B. Dirks, M. E., and constituted the basis for his graduate work.

Bulletin No. 2, Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and H. B. Dirks, giving the results of these experiments, was published in January, 1906. These tests were made with eight different brands of tool steel on cast-iron test pieces of varying hardness. The hardness of these test pieces was obtained by the use of a twist drill weighted to a known pres-

sure and run at a constant speed, the degree of hardness being based on the depth to which the drill would enter in a given time.

The work was divided into several sets of tests, viz., preliminary trials; skin-cut trials; endurance trials; trials to obtain the durability of the steel at different cutting speeds on cast iron of constant hardness; and trials to obtain the durability of the steels on cast iron of varying hardness. Tables giving in full the results of these different tests are supplemented by plates showing graphically some of the following relations: cutting force on point of tool and area of cut for cast iron of varying hardness; durability of tool and cutting speed for cast iron of varying hardness; cutting speed in feet per minute and hardness of cast iron.

From the last mentioned it was found that all the steels tested can remove very hard cast iron at 25 feet per minute, that all steels begin to wear rapidly at speeds a little above 125 feet per minute, and that between these two points there seems to be a definite relation between the hardness of the iron and the cutting speed. The general results show that there are great possibilities ahead for high-speed steels. Tool steels are now available that will cut cast iron from two to three times as fast as was possible a few years ago.

Circular No. 2, Drainage of Earth Roads, by Ira O. Baker, practically a reprint of *Agricultural Experiment Station Bulletin No. 65*, was issued in February, 1906, for the use of the Good Road Train of the Chicago and Alton Railway Company, at the expense of the latter.

Experiments are in progress under the direction of the department of Civil Engineering on the holding power of the various forms of plain and screw railroad spikes in treated and untreated timber with the view of determining the most efficient method of fastening the rails to the ties,—an important matter since the hard woods are now almost exhausted, and attention must be given to the softer woods.

Experiments on the collapse of boiler tubes are in progress by the department of Physics. For these tests the Bethlehem Steel Company has furnished a hollow nickel-steel tube, twelve feet long, with an internal diameter of five inches, capable of withstanding an internal pressure of 6000 pounds per square inch. A special pump capable of producing a pressure of 15,000 pounds per square inch has been imported for these experiments. The

department is also investigating the subject of measurement of high temperatures, such as are found in boiler and other furnaces used in industrial works. Both recording and optical pyrometers are being studied.

IV. Character of the Work to be Undertaken

In determining the character of the work which the station shall undertake, the most careful consideration will be given to the needs and the interests of the state. At the same time we shall not forget the debt which Illinois owes to her older sister states or to foreign nations for furnishing freely the results of scientific investigations or experimental determinations, making it possible for Illinois more cheaply to construct its railroads, mine its coal, generate its power, harvest its crops, communicate with its neighbors, and build its factories, its public buildings and its homes.

The work of the station will also be largely determined by the funds and facilities which are available for its work. It will seek the cooperation of all the industrial enterprises of the state, both great and small, and it will give help along those lines that promise to aid the greatest number of its people.

The work of the station should also extend into some fresh fields, seeking to discover new ways and means for economizing energy and materials, for the prevention of waste, for the perfection of labor-saving machinery, for safer methods of travel, and for surer sanitary methods of water supply and sewage disposal.

As an indication of the character of the work which it is proposed to do, the following short titles are given of some of the most important investigations which have been submitted for the approval of the station staff.

By the Department of Architecture

1. Insulating walls and materials to prevent transmission of sound, heat, dampness, etc.;

2. Resistance of hollow concrete building blocks to transmission of heat, sound, dampness, etc.;

3. Transmission of heat, light and sound through several thicknesses of glass in windows;

4. Comparative strength of wooden beams in tension, spliced in various ways;

5. Strength of compound (flitched) steel and wooden beams;
6. Strength of built-up wooden girders;
7. Syphonage of traps and its prevention;
8. Collection of best plans for small country schools;
9. Collection of best plans for farm houses and buildings.

By the Department of Civil Engineering

1. Tests of road-building materials;
2. Tests of angles riveted by one leg;
3. Effects of punching, reaming and boring upon different grades of steel.

By the Department of Electrical Engineering

1. Advantageous rates of acceleration for passenger and freight service;
2. Loss from braking, and its partial recovery by raising the level of regular stopping points;
3. Increased tractive effort due to winds in various directions;
4. Possible utility of some form of transmission or speed-changing ratio between motor and car for overcoming grades;
5. Economical lighting of large halls;
6. Determination of the minimum candle-feet required for comfortable reading with lamps of different color values;
7. Methods for increasing the time efficiency of long distance lines.

By the Department of Mechanical Engineering

1. Experiments with high-speed tool steels (continued);
2. Boiler trials with Illinois coals (continued);
3. Transfer of heat through scaled boiler tubes;
4. Comparative economy of domestic coals for residence heating;
5. The economy of municipal power and pumping plants;
6. Experiments with superheated steam;
7. Experiments with gas producers.

By the Department of Physics

1. Resistance of boiler flues to collapse;
2. Heat conductivity of walls of buildings;
3. Appliances for measuring high temperatures under furnace conditions;

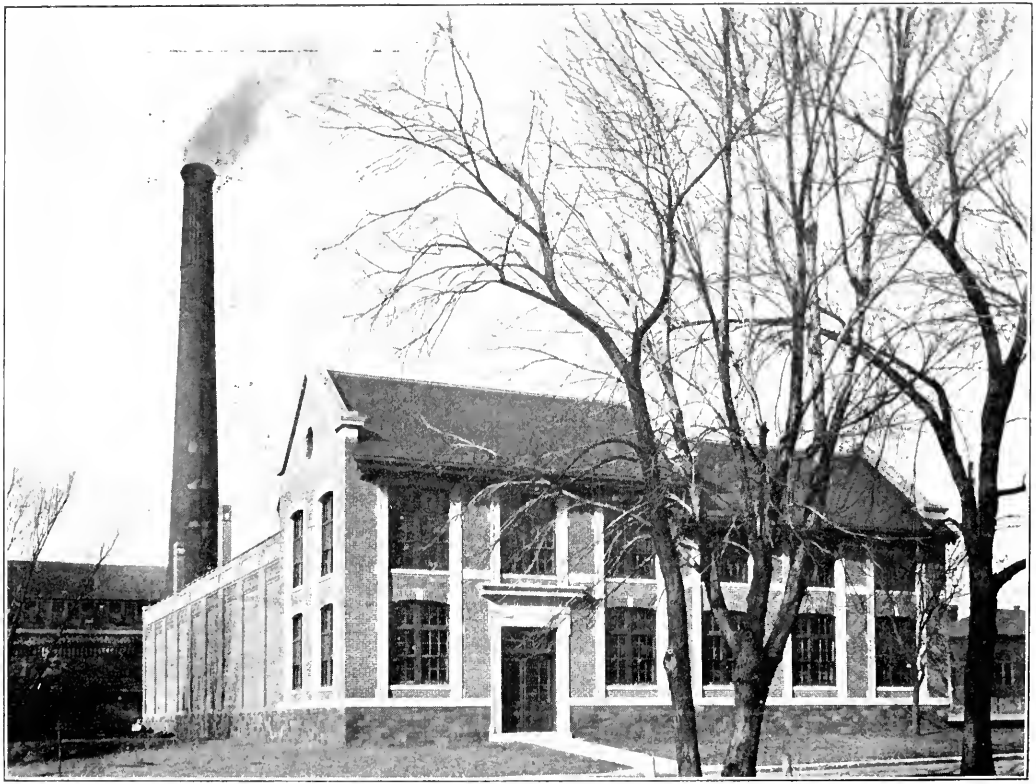


FIG. 1 MECHANICAL ENGINEERING LABORATORY
BUILT IN 1905

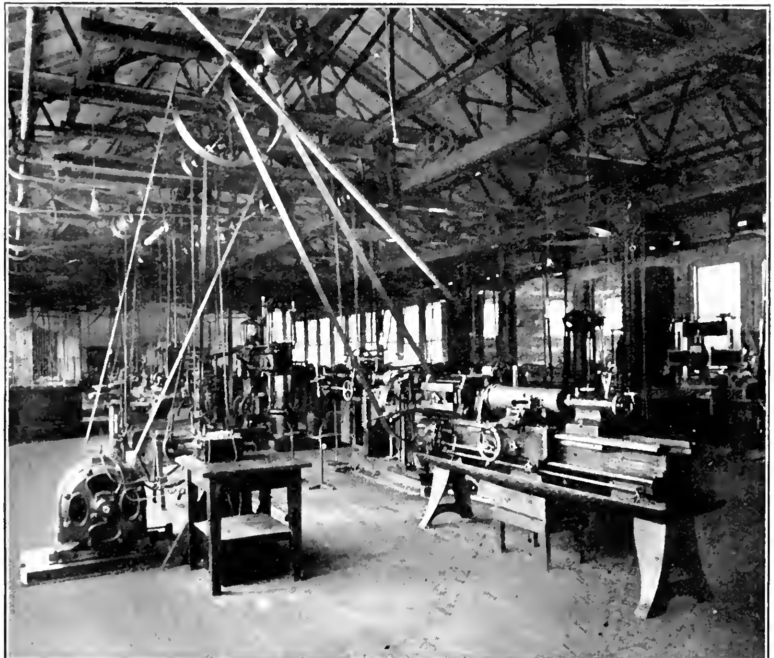


FIG. 2 VIEW IN THE UNIVERSITY OF ILLINOIS MACHINE SHOP SHOWING LOCATION OF LATHE AND MOTOR DRIVE USED IN TESTS WITH HIGH-SPEED TOOL STEELS

4. Determination of vapor densities at very high temperatures and high pressures.

By the Department of Railway Engineering

1. Locomotive road tests and railway train resistance.

By the Department of Theoretical and Applied Mechanics

1. Reinforced concrete beams (continued);
2. Reinforced concrete columns;
3. Timber stringers;
4. Cast-iron columns;
5. A series of tests of interest to manufacturers and railroads on such structures as car bolsters, car frames, wheels, etc.;
6. Qualities of commercial mild steels;
7. A series of investigations on various hydraulic problems;
8. Deep well pumping.

From the above list it will be seen that there exists a very large field for fruitful research. In many cases these investigations must extend over a series of years; in others a few months will suffice for the work.

V. Facilities For Investigation

The recent rapid growth in attendance in the College of Engineering has made it necessary to extend its equipment considerably, and while the apparatus thus provided is intended primarily for purposes of instruction, much of it is available at certain times of the year for purposes of investigation. Certain appliances have recently been purchased and installed for the especial use of various departments in connection with such investigations as are in progress in these departments.

The Engineering Experiment Station is not quartered in any one building of the College of Engineering, but its work and experiments go on wherever the needed facilities exist in the various departments. Neither is its work confined to the College of Engineering alone. Cooperation with other University departments, such as the College of Science, State Water Survey and with the State Geological Survey enables it to complete many investigations, facilities for which are not available within the College of Engineering. Neither is its work confined within the limits of the University. Cooperation with various departments of the

federal government as well as with many industrial interests of the state is already assured.

On the following pages are mentioned some of the most important appliances which are available for use in various lines of research. Only a few words of description are possible with reference to each. In connection with this article are given several reproductions showing the laboratories in which the investigations are in progress, and also the most important apparatus.

In the Mechanical Laboratory

1. A 210 H. P. Heine water-tube boiler especially arranged for testing Illinois coals. This boiler is a duplicate of the boilers being used at St. Louis by the United States government in testing coals from various parts of the country. A Green chain grate stoker is installed under this boiler, and draft is furnished by a Sturtevant induced draft fan, drawing the gases through an economizer. The chain grate under the boiler may easily be removed and a plain furnace for hand-firing substituted. A complete equipment of auxiliary apparatus necessary for boiler tests is available, including recording and optical pyrometers, and standard and recording apparatus for continuous gas analysis. Facilities are now available in the department of Physics for calibrating all thermometers and pyrometers used in work of this character.

2. An independently-fired Foster superheater capable of superheating the steam from a 150 H. P. boiler 300° above its temperature at 120 pounds gauge.

3. Several residence heating boilers, for both steam and hot water. These boilers will serve to compare the values of such various coals as are offered in the Illinois market for domestic purposes.

4. A 10-ton York refrigerating plant for the production of cold or for specific tests. With this plant there are 17 cans for ice making, each holding 100 pounds. The possibility of subjecting various building stones or other material to alternate freezing and warming is worthy of consideration. The effect of fifty winters might thus be known in a single month.

5. A liquid-air plant with a capacity of about three quarts an hour. It consists of a Norwalk four-stage compressor, compressing up to 3000 pounds, together with a Hampson liquefier with facilities for temperature determinations.

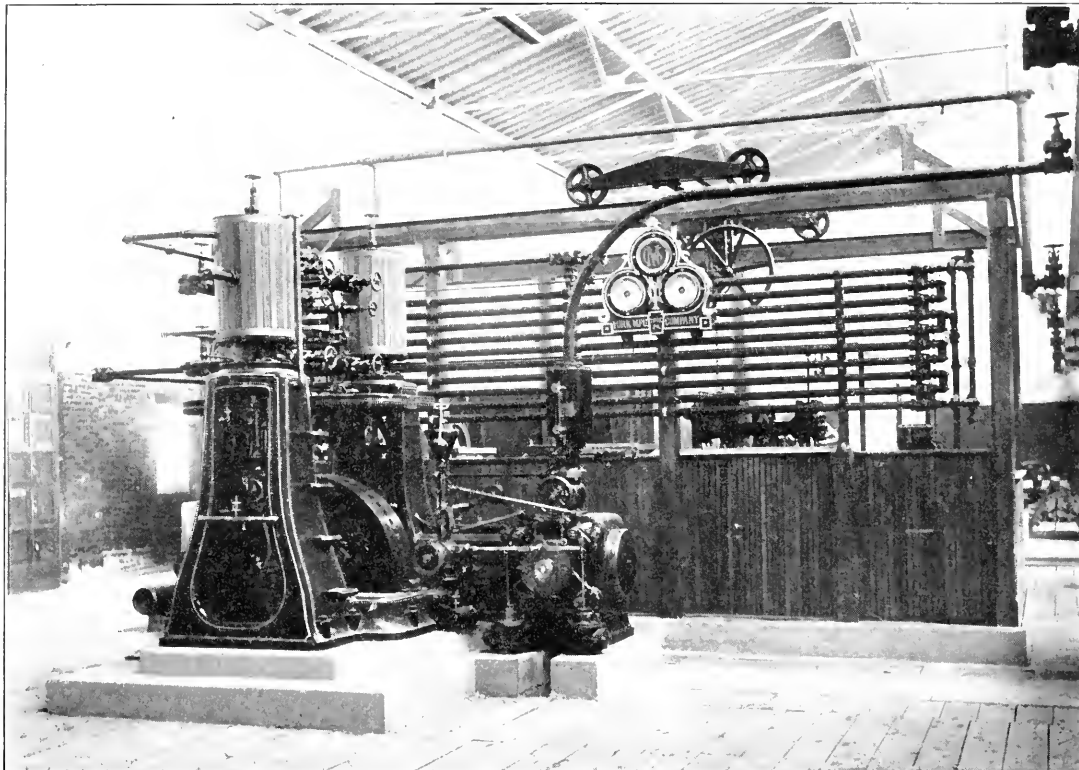


Fig. 3 York Ice Machine of 10-ton Refrigerating Capacity in Mechanical Engineering Laboratory

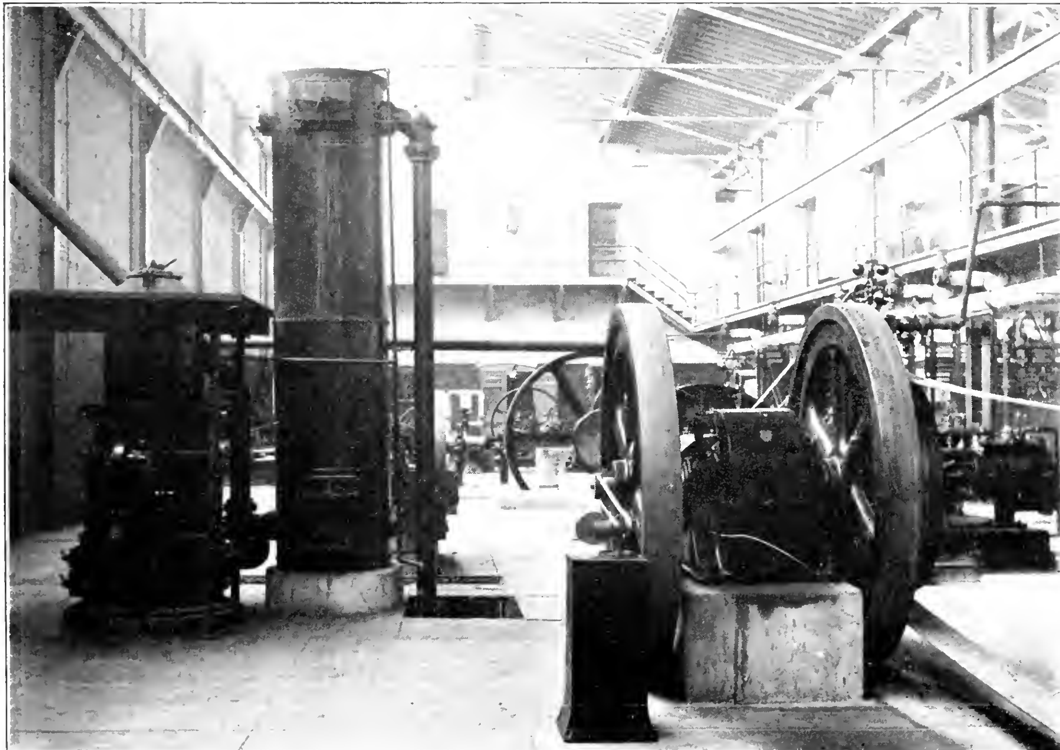


Fig. 4 Otto Gas Producer and Gas Engine in Mechanical Engineering Laboratory

6. An Ingersoll-Sergeant two-stage air compressor driven by compound steam cylinders. The steam cylinders are 12 inches and 22 inches in diameter with a 12-inch stroke, and the air cylinders are $12\frac{1}{4}$ inches and $18\frac{1}{4}$ inches in diameter with a 12-inch stroke. A vertical receiver 42 inches by 8 feet high is provided for use with the compressor.

7. A 50 H. P. suction gas producer built by the Otto Gas Engine Works. This producer is adapted to burning anthracite pea coal, coke or charcoal.

8. An Otto gas engine of 23 brake H. P. capacity for use in connection with the gas producer. The cylinder is 10 inches in diameter, with a 19-inch stroke. It is provided with a compressed air starting device, sparking generator, speed indicators and all other instruments necessary for testing gas engines.

9. A 15 H. P. De Laval steam turbine direct-connected to a compound centrifugal pump. This apparatus will deliver 140 gallons of water per minute when pumping against a head of 500 feet. The turbine wheel and small pump runner make 23,500 revolutions per minute; the large pump runner makes 2350. The turbine is provided with condensing and non-condensing nozzles.

10. A hot blast heating system installed to heat the Mechanical Engineering Laboratory. This consists of a series of coils making 2800 feet of 1-inch pipe and a 72-inch fan draw the air through the coils and force it into the galvanized iron pipe, 36 inches in diameter, which distributes it to different parts of the building. The fan is driven by a small vertical steam engine.

11. A 100 H. P. Allis-Chalmers Corliss engine, equipped with a suitable brake and other apparatus for making tests.

12. Several high-speed steam engines for testing and for driving other apparatus.

13 Several types of gasolene engines, ranging from 1 to 10 H. P., for experimental purposes.

14. An automobile testing platform for testing automobiles.

15. A 10-ton electric crane, having three alternating current motors, for experimental work.

16. A Golden oil testing machine for testing lubricating oils and bearing metals.

17. Apparatus for tests relating to the transmission of heat through scale-covered boiler tubes with respect to the loss due to scale. The equipment now in the Mechanical Engineering Lab-

oratory for determining the loss due to the scale when transmitting heat through scale-covered tubes consists of a boiler and furnace giving approximately practical conditions, also auxiliary apparatus for making the required observations. The furnaces employed are constructed of wrought iron suitably covered, or of brick with fire-brick lining, and are equipped with gas burners for the generation of the required heat. From the furnace the hot gases pass through the tube which is being tested. This tube constitutes the single flue of the experimental boiler. The boiler is filled with water continually entering and leaving at temperatures maintained constant. The auxiliary apparatus used consists of constant-pressure tanks for air, gas and water, suitable thermometers, pyrometers, scales, etc., a Le Chatelier pyrometer being used to measure the temperature of the hot gases entering the tube.

RAILWAY TEST CAR NO. 17

18. This railway test car is a special car operated for experimental and instructional purposes. It is owned jointly by the Illinois Central Railroad and the University of Illinois. It was built by the railroad company, equipped by the University and is operated for the advantage and information of both. It is considered by the University as a part of its laboratory equipment, and affords facilities for practical railroad tests which could not otherwise be made.

The car is used principally in connection with dynamometer car work, and on this account was built especially heavy in order to withstand the usage incident to this kind of work. It is $45\frac{1}{8}$ feet in length. A space of about 15 feet in the rear of the car is occupied by berths and lockers, the remaining space being devoted to apparatus and instruments.

The dynamometer is of the hydraulic or oil transmission type. It consists of three cylinders in tandem, and is situated near the forward end of the car just back of the draft rigging. The dynamometer is suitably connected with a recording instrument which gives the draw-bar pull record upon paper traveling at a rate of speed proportional to the speed of the train. Upon the same paper records are made of time, speed, distance and such other data as may seem desirable. In addition to the dynamometer with its attached recording instrument, paper travel mechanism, gauges and similiar apparatus, the car is equipped with a Boyer speed recorder, a Hausshalter speed recorder, rec-

ording gauges for steam pressures, train line pressures and draft, also with air and steam pressure gauges for various purposes.

In its capacity as a dynamometer car. Railway Test Car No. 17 affords facilities for work along the following lines:

Tonnage rating tests;

Engine efficiency tests:

Tests in relation to engine design and tractive force:

Tests to determine resistance of freight, passenger, loaded or empty cars;

Tests to determine resistance of trains as affected by speed, curves, temperatures, condition of track or special equipment.

Aside from its use as a dynamometer car, when no draw-bar pull record is desired, the car is used in connection with locomotive road tests or other road tests, records being made in the car automatically or otherwise that without the car would not be attempted or could be made only with difficulty. Further the car serves a most useful purpose as office, laboratory and computing room when making railroad or other shop tests in connection with railway work.

This car has already been in extensive use on the Illinois Central Railroad for the purpose of making locomotive road tests, and for establishing tonnage ratings on the various divisions. The preliminary experimental work relating to train resistance in connection with the electrification of the New York Central lines out of the Grand Central Depot, New York City, was all done with this car. A series of tests has also been made with this car comparing the relative draw-bar pull and acceleration factor of steam and electric locomotives on the experimental tracks of the General Electric Company at Schenectady, New York. Both of these tests have been reported to the American Society of Electrical Engineers in a paper by B. J. Arnold at the annual meeting 1904.

In the Road-Materials Laboratory

The Civil Engineering department in its Road-Materials Laboratory is equipped with apparatus for testing materials for road and pavement construction as follows:

(a) Two types of rattlers for testing brick: National Brick Manufacturers' Association and Talbot-Jones:

(b) A Dorrey, a Deval and a Page machine with the neces-

sary accessories for testing the road-building qualities of gravel and macadam. The laboratory is cooperating with the State Highway Commission and with the State Geological Survey in a systematic study of the road-building materials of Illinois.

In the Cement Laboratory

This laboratory is equipped with briquette molds, molding machines, testing machines, etc., necessary in testing hydraulic cement, and in making investigations as to the effect of different materials and methods of manipulation upon the strength of mortars and concrete.

In the Laboratory of Applied Mechanics

1. A Riehle vertical screw power testing machine of 600,000 lb. capacity fitted to take large and bulky test specimens. This machine will take compression pieces 25 feet long and tension pieces of the same net length except as allowance must be made for stretch. The clear distance between screws is 36 inches, which gives room for bulky and built-up pieces. The machine is provided with a stiffened vertical frame to allow eccentric and oblique forces to be applied to test pieces, an unusual feature in testing machines. Short beams may be tested on the machine, and provision may easily be made for testing longer beams. Auxiliary appliances are used for holding the various forms of test piece in order to secure an application or distribution of the load in the manner desired. Especial attention was given in the design and construction of the machine to making it applicable to a large range of tests. The calibration of the machine shows that it is very accurate and very sensitive. For the smaller loads a second poise weighing up to 60,000 lb. is used.

2. An Olsen four-screw testing machine of 200,000 lb. for tests in tension, compression and flexure. This machine will take beams up to a length of 20 feet.

3. Three 100,000-lb. testing machines of different makes, fitted up in the usual way.

4. An Olsen torsion machine of 220,000 inch-pound capacity.

5. An Olsen vibratory testing machine for testing stay bolts.

6. A variety of smaller machines for testing cast iron, timber, etc.

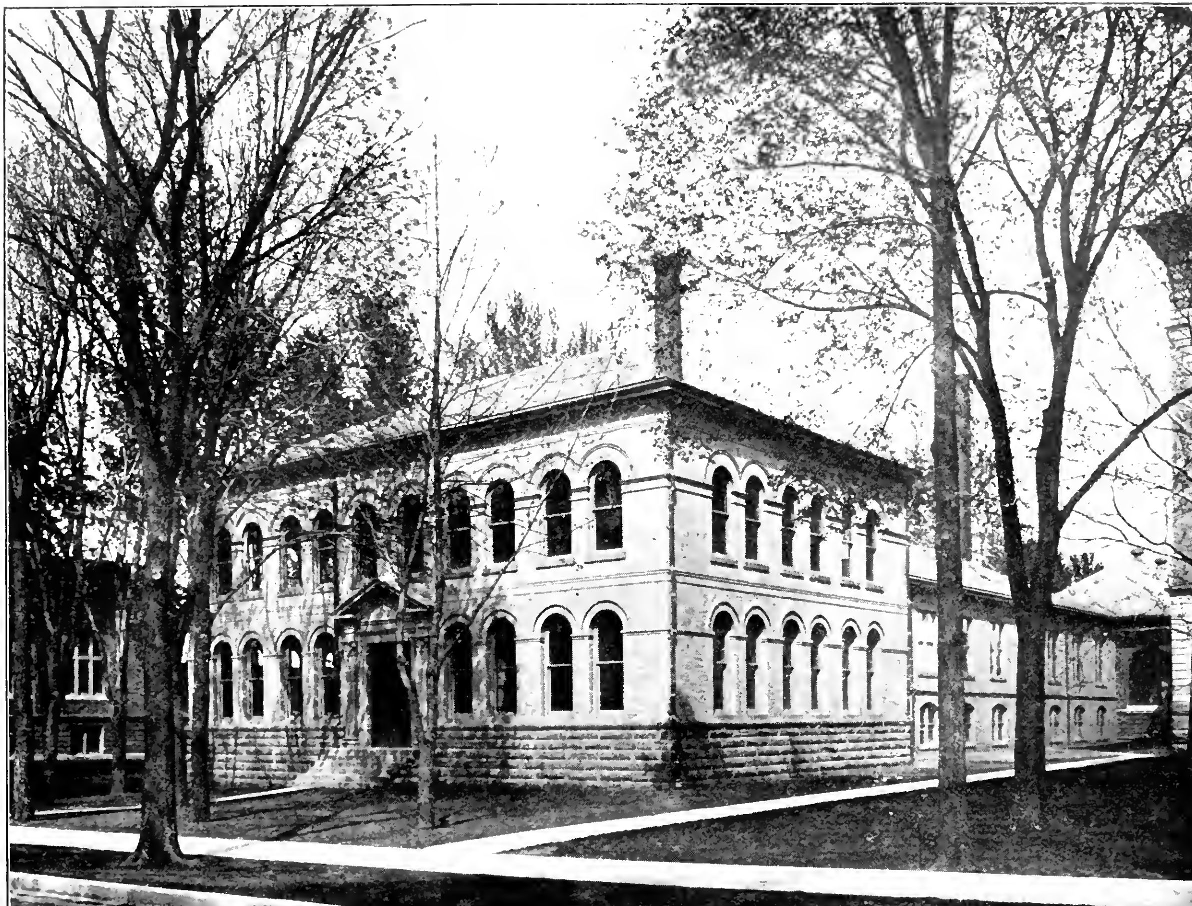


Fig. 5 Laboratory of Applied Mechanics
Built in 1901

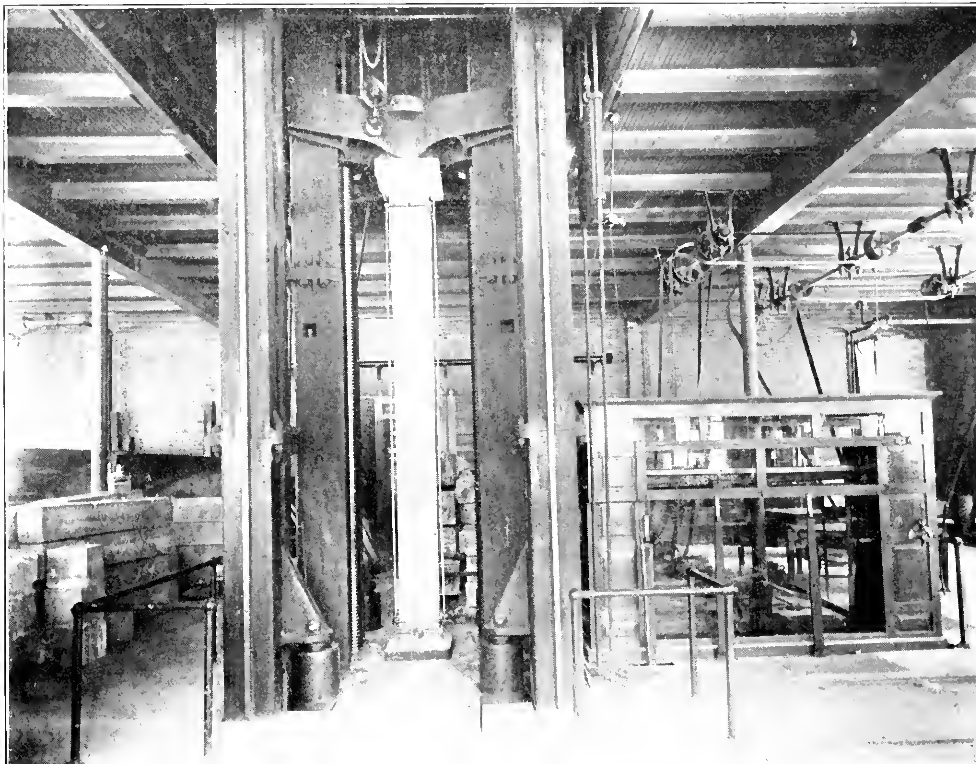


FIG. 6 TESTING 12 x 12 IN. CONCRETE COLUMN IN 600,000-LB. TESTING MACHINE

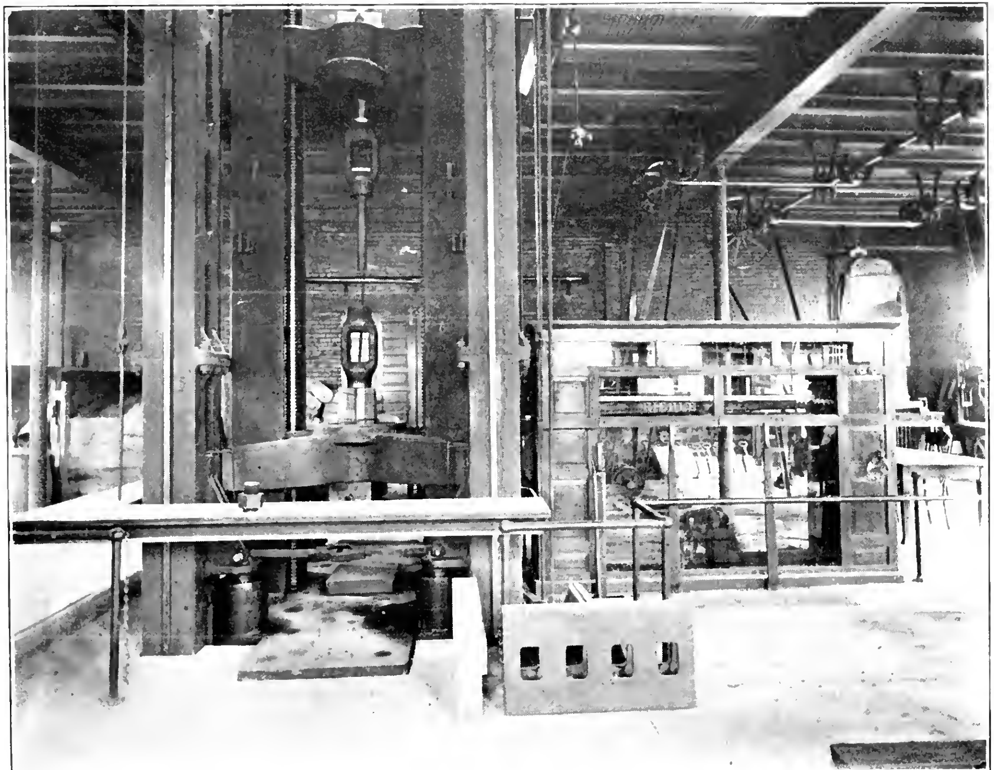


Fig. 7 View Showing 600,000-lb. Testing Machine as Used in Tension Tests

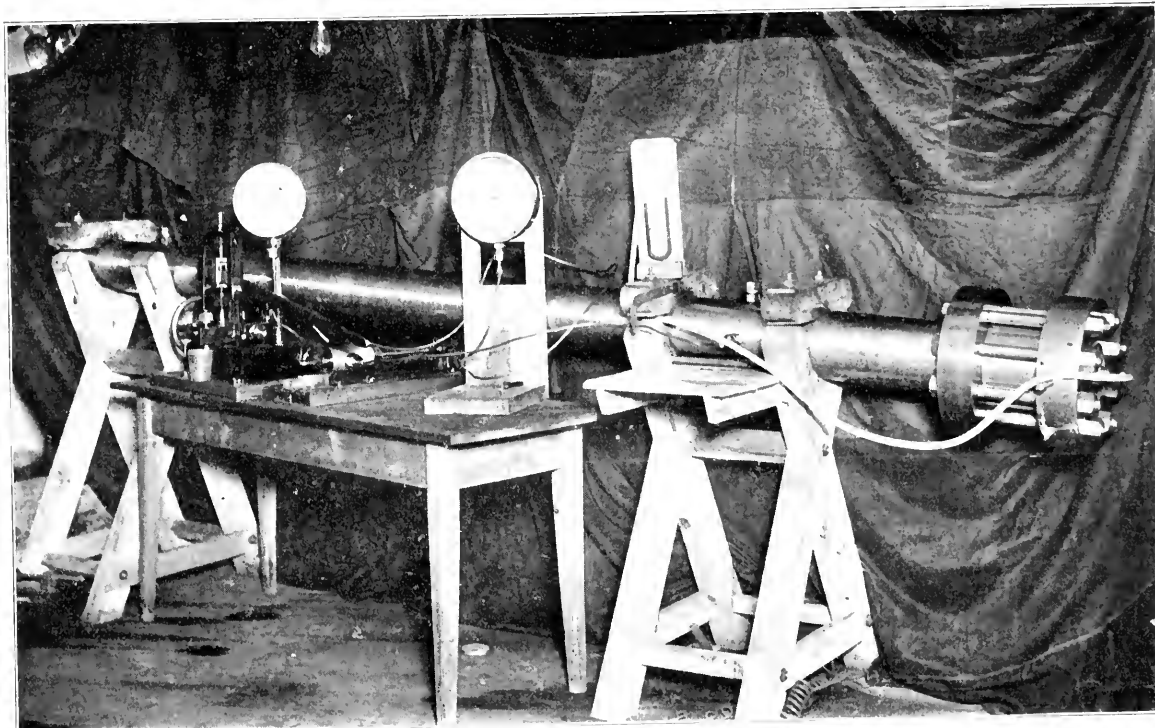
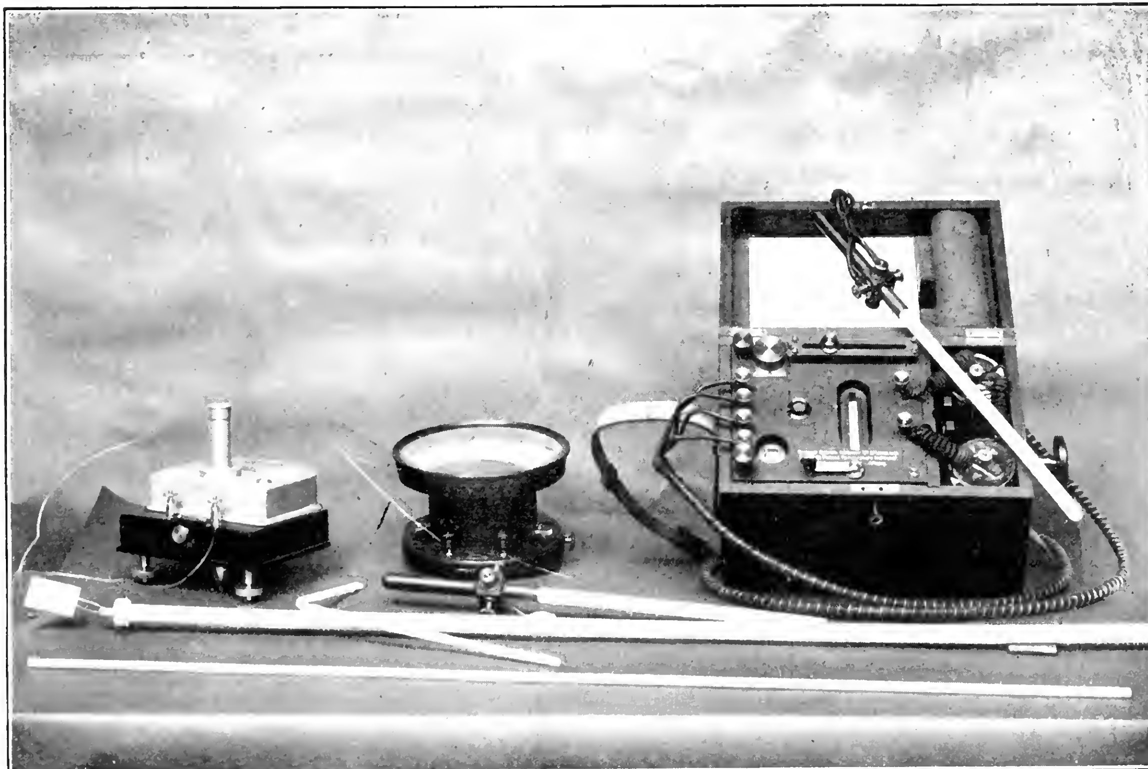
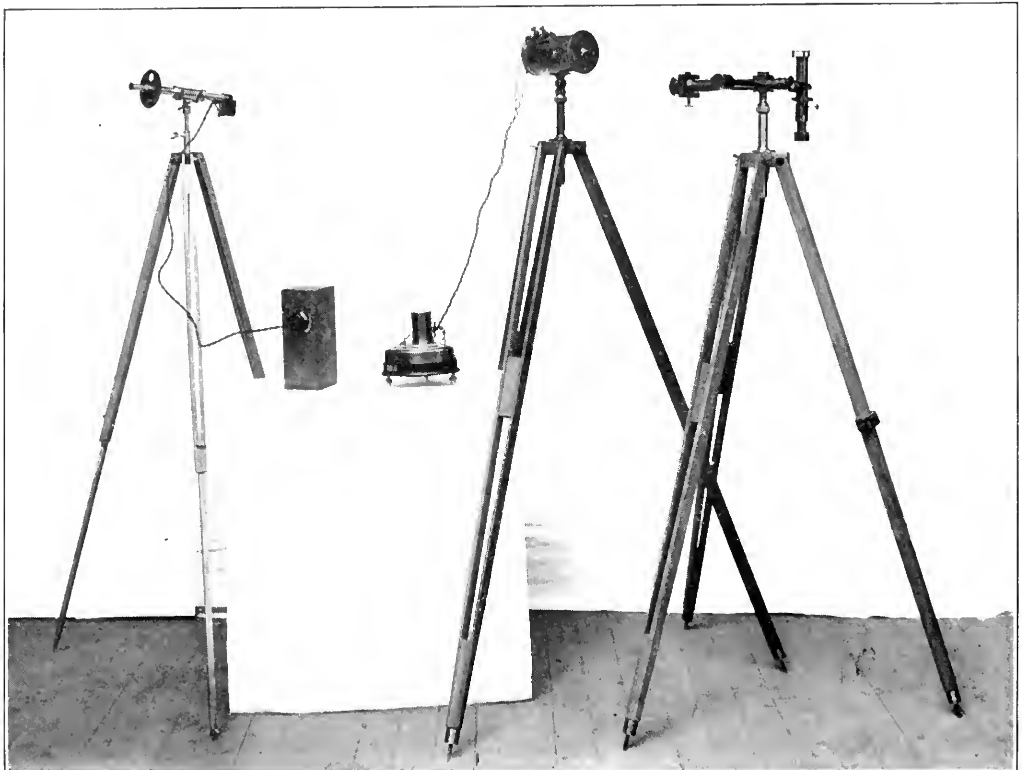


FIG. 8 APPARATUS FOR COLLAPSING BOILER TUBES



THERMO-ELECTRIC PYROMETERS CALLENDAR RESISTANCE PYROMETER

FIG. 9 ELECTRICAL PYROMETERS



WANNER FERY CHATELIER

FIG. 10 OPTICAL PYROMETERS

7. A large equipment in measuring devices such as extensometers for various uses, autographic recording devices, gauges, etc.

8. A commodious hydraulic laboratory, well equipped with steam engine, steam pumps, centrifugal pumps, standpipe and pressure tanks, lines of piping, measuring pits, tanks, weirs, gauges, meters, motors, etc., giving excellent facilities for testing hydraulic apparatus and for making investigations in hydraulics.

IN THE PHYSICS LABORATORY

The Physics department is equipped with apparatus enabling it to do the following work in testing and standardization:

1. The testing of boiler tubes for collapse;
2. The checking and calibration of instruments for measuring temperatures;
3. The checking and calibration of electrical standards and instruments;
4. Miscellaneous physical testing.

The Testing of Boiler Tubes.—The apparatus available for this work consists of a nickel-steel tube, part of a United States naval gun, capable of withstanding about 20,000 pounds per square inch internal pressure. This apparatus permits of the testing of flues and tubes up to 3½ inches diameter and 10 feet in length for resistance to collapse under external pressure. It is in use at the present time for the determination of a formula for predicting the failure of steel tubes under pressure. Pressures up to 14,000 pounds per square inch may be produced by means of a Cailletet pump, made by the Societe Genevoise, Switzerland. Upon the completion of the work now in progress, the apparatus will be maintained intact for testing at any time the constants of flues and tubes.

The Checking and Calibration of Instruments for Measuring Temperatures.—The department has facilities for testing and checking thermometers and pyrometers.* Standard thermometers of the best make, graduated to 0.1° C. and certified by the Reichsanstalt, permit of tests between –25° C. and 250° C. Special con-

*Pyrometers,—Electrical: resistance type, *Callendar recorder with Whipple indicator*, Cambridge Scientific Co., Ltd., Cambridge, England: thermo-electric type, Siemens & Halske, Berlin, Germany; Hartmann & Braun, Frankfort-on-the-Main, Germany; *Bristol*, W. H. Bristol, 41 Dey St., New York City. Optical: *Wanner*, American agents, Eimer & Amend, 205 Third Ave., New York City; *Fery* and *Chatelier*, Ph. Pellin, Paris, France.

stant temperature baths are being made for the convenience and rapid comparison of thermometers.

The equipment for pyrometry is the best obtainable. The department owns a Callendar recorder of the laboratory type and a Whipple indicator with a series of platinum resistance thermometers ranging from 0° C. to 1200° C. In addition to these electric resistance pyrometers, a series of thermo-electric pyrometers is available for checking and testing other pyrometers. The thermo-electric couples with Reichsanstalt certificates are calibrated for temperatures from -180° C. to 1600° C.

The laws of the relation of temperature, light and radiation, have within a few years been studied, so that it is now possible to measure temperatures by optical methods. The equipment in optical pyrometry consists of the Le Chaletier, the Wanner and Fery radiation pyrometers.

For the production of extreme temperatures, both low and high, the department is provided with a liquid-air machine, and with electric furnaces of the arc and of the resistance types. A specially protected constant temperature room has been provided for work of all kinds requiring constancy of temperature.

Electrical Standards and Apparatus.—The department owns certified standards of resistance, electromotive force and inductances, and its cabinets contain apparatus of the best make for all electrical and magnetic testing. The Kelvin ampere balances, Weston standard and semi-portable voltmeters and ammeters, and Siemen's electrodynamometers of the department are frequently checked by the potentiometer with standardized resistances and Clark and Weston cells. The laboratory is supplied not only with apparatus but also with piers and conveniences for these tests.

Miscellaneous Testing.—Besides the equipment for the work in the three lines indicated above, the department of Physics is supplied for its instructional and research work with standard apparatus of a variety of kinds, all of which is available for testing purposes. Such facilities are standard barometers, standards of length, photometric standards with photometers, standards of weight with sensitive physical balances, a dividing engine and comparator, vacuum and compression pumps with gauges, and various optical apparatus.

In the Electrical Laboratory

The Electrical Laboratory occupies a separate building and contains an excellent equipment available for many lines of research. It will not be possible to give any detailed description of this equipment but some of the more prominent facilities are mentioned below.

1. In the basement is a storage battery (Gould) of 60 cells each of 240 ampere hours' capacity. This is wired so that all voltages between 2 and 120 can be obtained; also current up to 100 amperes at full voltage, with greatly increased current at lower voltages. This battery is especially adapted to the calibration of electrical measuring instruments, the testing of fuse wire, and to all work where steady current is required.

2. The dynamo laboratory contains very complete arrangements for testing any of the usual types of machines. Power is supplied mostly at 220 volts D. C. and at 440 volts, two-phase A. C., but the transformers permit other usual voltages to be supplied. Several types of variable speed motors, having a speed range from 300 to 1200 revolutions and giving 15 H. P. at any speed, are a recent addition to the equipment. Two general electric stationary armature alternators, capable of connection as either two or three-phase generators or motors and at a variety of voltages, are available. Three rotary converters furnish current based on 110 and 500 volts D. C. An inductor alternator, built by students and designed primarily for variable frequency experiments, may be run at various frequencies up to 150.

There are also switchboards for the rapid handling of apparatus; numerous lamp banks for resistance; a small electric welding machine; various types of arc lamps, permitting experiments in lighting; inductances, condensers, and a large range of measuring instruments of all kinds.

3. A laboratory for the study of illumination is equipped in connection with the photometer rooms. Shades like wall maps line the walls, whereby a light or dark effect can be obtained. This room is lighted by both ceiling and bracket fixtures. Two photometers are available for testing globes and shades as well as lamps of various types. The efficiencies of different types of shades have been studied, also the flickering effect of alternating lighting. Some interesting developments have been made in curved coherers for space telegraphy.

4. A telephone laboratory of two rooms permits experiments in telegraphy and telephony. Experiments now in progress seem to show the availability of high-tension wires for the transmission of telephone messages, obviating the need for separate telephone wires on power lines. Some improvements in long-distance telephony are being tested.

5. An electric test car is also a part of the equipment. This is an interurban type of car, built by the Jewett Car Company, and equipped with the latest type of multiple-unit control 500 volt D. C. motors, by the Westinghouse Electric and Manufacturing Company. One end of the car contains the switch group operated by compressed air, and also the measuring instruments for determining voltage, current speed and acceleration. The car has four 50 H. P. motors, double trolley and controllers at each end of the car, and the usual equipment of head lights, air brakes, heaters, etc.

With this car determinations of the power required for the hauling of coal on electric roads are in progress, and a comparison will be made with the results of dynamometer car tests on steam roads. Traction experiments on a large scale are possible through the courtesy of the Illinois Traction System, whose line passes through the University grounds. The recent equipment of the electric test car of 200 H. P. with recording electric instruments will allow the determining with considerable accuracy of the power required to operate at different speeds and over different grades and curves. A subject of investigation will be the normal highest speed that corresponds to a given radius of curvature, from which it will be possible to determine how much a sharp curve will retard a car.

VI. The Industrial Interests of Illinois

The state of Illinois is singularly favored in all the conditions requisite for a rapid and permanent industrial development. It has a vast area underlaid with productive coal seams, which afford an abundant supply of bituminous coal of good quality. With the Great Lakes on the northeast, the Mississippi river on the west, and with a network of railroads having an aggregate length of nearly 12,000 miles, facilities for transportation are unexcelled. Illinois is also fortunate in its large area of arable land of extreme fertility. In view of its cheap and abundant fuel and its unex-

FIG. 11 ELECTRIC TEST CAR

Fig. 12 Electrical Engineering Laboratory
Built in 1897

celled facilities for the transportation of raw material and finished products, it is not surprising that Illinois has pushed forward rapidly in manufacturing and allied industries. Since 1850 the growth of manufacturing in Illinois, measured by the value of the manufactured product, has been at an average rate of one hundred per cent a decade, and the rank of the state has advanced from fifteenth to third. This rate of advance is typical of the development in other industrial lines.

The industrial interests of Illinois may be grouped in four chief classes:

1. Agriculture
2. Coal and Mining
3. Transportation
4. Manufacturing

Of the five million inhabitants of Illinois, more than one-third are engaged in remunerative occupations. A rough idea of the distribution of workers among the industrial pursuits outlined above may be gathered from the following statement. According to the census of 1900, the working population of Illinois may be divided into four nearly equal parts, one of which is engaged in agricultural pursuits; one, in manufacturing; one, in trade and transportation; the last, in domestic and professional service. In the following pages the various industrial interests will be considered somewhat in detail.

Agriculture.—In the value of agricultural products, Illinois ranks second, having been exceeded in 1900 by Iowa. The value of agricultural products for 1900 was $345,650,000. This is slightly less than 28 per cent of the value of manufactured products for the same year. From the nature of things, the value of agricultural products after reaching a certain stage can increase but little, while there is practically no limit to the value of manufactured products. Hence while Illinois will always hold high rank in agriculture, its preeminence in the future will be due to its manufacturing and transportation industries.

Coal.—The coal deposits of Illinois are included in the eastern interior coal field of the United States, which covers western Indiana, nearly the whole of the state of Illinois, and western Kentucky. Illinois has the largest coal-bearing area of any state in the Union, about two-thirds of the state, or upwards of 37,000

square miles, producing coal. A medium grade of bituminous coal is mined, suitable for the production of power, being used mostly as a steaming fuel by railroads and manufactories.

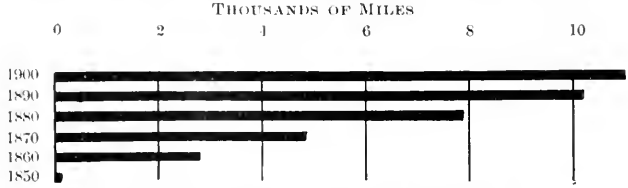
Outside of Pennsylvania, which is preeminently the first state in coal mining, Illinois leads in the production of coal, yielding about one-eighth of the entire quantity mined in the United States. The following table shows the production of coal in the leading coal states during 1902 and 1903:

PRODUCTION OF BITUMINOUS COAL IN THE UNITED STATES

Rank	State	1902	1903	Increase Per Cent
1	Pennsylvania	98,946,000	103,000,000	4
2	Illinois	30,031,000	34,955,000	15
3	West Virginia	26,162,000	26,882,000	2.7
4	Ohio	23,929,000	24,573,000	2.6
	United States	258,372,000	277,077,000	6.7

The following statistics for the year ending June 30, 1903, will give an idea of the magnitude and importance of the coal industry in Illinois: During that year there were 935 mines in operation, giving employment to 35,000 miners and 15,000 employees other than miners. The total product was 35 millions of tons, valued at more than 36 millions of dollars at the mines.

Railroads.—In the aggregate of its railway mileage, Illinois holds first rank among the states of the Union, although Texas is a close second. The rapid development of railroads in Illinois is doubtless due to some extent to the early establishment of Chicago as a distributing center of eastern products to the west and southwest. Chicago became the outlet of the traffic by way of the Great Lakes, and when the era of railroad building succeeded, naturally became a great gateway between eastern and western trunk lines. As a result, Illinois is traversed by railroads in all directions. The accompanying charts show the growth of mileage in Illinois since 1850 and the mileage in several states.



MILEAGE GROWTH OF ILLINOIS STEAM RAILROADS

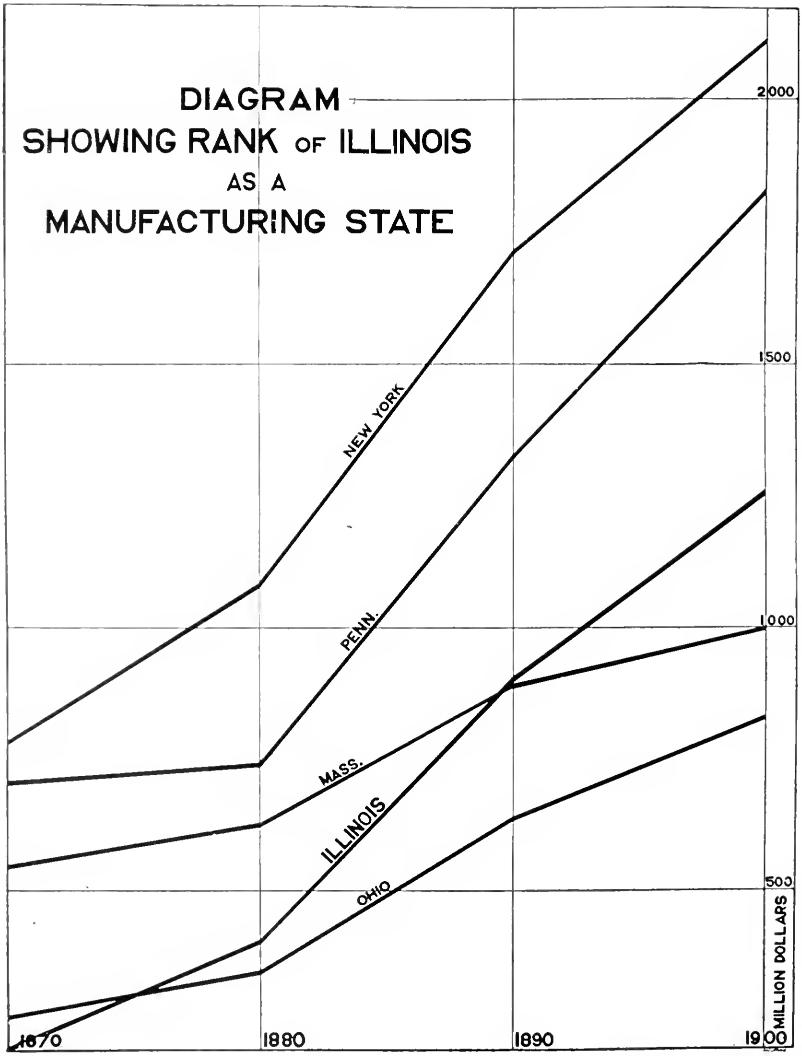
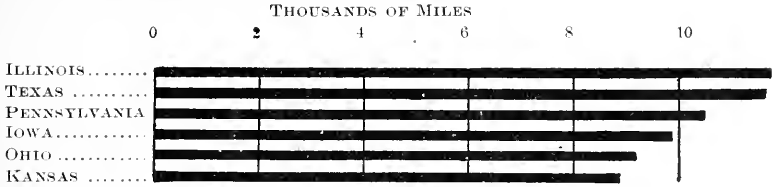


DIAGRAM
SHOWING RANK OF ILLINOIS
AS A
MANUFACTURING STATE
NEW YORK
PENN.
MASS.
ILLINOIS
OHIO
2000
1500
1000
500
MILLION DOLLARS
1870
1880
1890
1900



STEAM RAILROAD MILEAGE IN SEVERAL STATES—1904.

The magnitude of the railroad industry in Illinois is evidenced by the car construction and repair bill. Thus in the statistics for manufactures for 1900, the items for cars and general shop construction, and repairs by steam and street railroad companies aggregate nearly $18,000,000.

In the mileage of street and electric railroads, Illinois is as yet somewhat behind some of the eastern states. In 1903 the mileage of street and electric railroads in several leading states was as follows:

Massachusetts	2037
Pennsylvania	2001
Ohio	1858
New York	1822
Illinois	993

It is significant, however, that the wave of development in electric railroads is sweeping westwards. In the last two or three years, great progress has been made in Ohio, Michigan and Indiana. Illinois has only fairly started in the building of interurban railroads, and the next ten years will doubtless witness a development along this line that will place it well towards the first rank.

Manufacturing.—In the value of manufactured product, Illinois at present ranks third among the states of the nation. The accompanying diagram shows the relative position for several decades of the five foremost states in manufacturing. The rapid rate of increase in the case of Illinois is worthy of attention.

Statistics for 1900 showed a total value of manufactured product of $1,260,000,000, an increase of nearly 40 per cent over the figures for 1890. The following table gives data selected from these statistics relating to leading industries somewhat allied in character to engineering:

INDUSTRIES	WAGE EARNERS	WAGES IN MILLIONS	VALUE OF PRODUCT IN MILLIONS
Agricultural implements............	18,231	9.06	42.0
Cars, shop constructions and repairs steam railroads..................	13,803	8.29	16.6
Cars, steam railroads, not including operations of railroad companies	9,314	5.36	24.8
Electrical apparatus and supplies...	6,048	2.82	12.2
Foundry and machine shop products	31,851	16.88	63.9
Iron and steel.	16,642	9.64	60.3
Vehicles (bicycles, carriages, etc.)...	9,300	4.40	18.0

In 1900 the number of manufacturing establishments in Illinois was 38,360, and the total number of people engaged in manufacturing was nearly 400,000. The wages paid amounted to $192,000,000, or nearly $500 per person employed. The value of the product, as has been stated, was $1,260,000,000. The total manufactured product for 1905 was probably over $2,000,000,000, an increase of sixty per cent in five years, which may be compared with the increase of forty per cent in the preceding ten years. In view of the present rate of increase in manufacturing, it seems not unlikely that in another decade, Illinois will be a sharp rival of New York and Pennsylvania for first rank.

VII. What Work Can The Engineering Experiment Station Do That Will Aid The Industrial Interests Of Illinois?

For a number of years the agricultural industry of the state of Illinois has been greatly benefited by the work of the Agricultural Experiment Station. During the first years of its existence, this experiment station was supported by the United States government in accordance with the provisions of what is commonly known as the Hatch Act, approved by Congress March 2, 1887.

Subsequently, the increasing demands upon the station for investigations of various kinds rendered additional funds necessary, and the state was called upon for assistance. At present, the Agricultural Experiment Station receives regular support from the state at the rate of about $85,000 per annum. The bennefits to agriculture resulting from the investigations of the station are too well known to need comment. The expenditures of the state in support of the station have been repaid many times. Millions of dollars have been added to the wealth of Illinois through the investigations on corn breeding, the soil surveys and fertility experiments, and the work of eradicating insect pests.

It is the hope of the station staff that the Engineering Experiment Station may stand in the same helpful relation to the great mining, transportation and manufacturing interests of Illinois. What has been done for agriculture may well be done for manufacturing. The state's investments in the Agricultural Experiment Station have been rewarded with large dividends in the way of increased soil fertility and increased and improved agricultural product. Surely as large dividends await similar investments in the Engineering Experiment Station. Important problems in agriculture have been and are being successfully solved by the Agricultural Experiment Station. Important and difficult problems of engineering confront the manufacturer and power user, and press for solution. It is the aim of the Engineering Experiment Station to assist in the solution of these problems, and thus to aid and uplift the engineering industries of Illinois. It may be well to call attention here to the rapidly increasing popularity and value of the work of the Royal Testing Laboratory, located at Charlottenburg, Germany, which has been doing for the German Empire work similar in some details to that which it is now proposed shall be done by the Engineering Experiment Station.

In the following paragraphs are discussed somewhat in detail the lines of work that may be taken up for the benefit of certain industrial interests.

Fuel.—The fuel supply of Illinois is of prime importance in its industrial development, and no effort should be spared in the introduction and promulgation of improved methods and processes in the production and consumption of coal. From broad economical considerations, wasteful methods of using coal, or the rejection of any combustible part as waste, are to be discountenanced. Exhaustive and careful experiments will be required before the best conditions can be attained. These experiments must include analyses of coals from all parts of the state, a determination of the best kinds of coal for specific purposes, best methods of burning Illinois coals, effects of various methods of preparation, experiments on various kinds of furnace construction, etc.

Generation and Use of Power.—Along the line of power production there is opportunity for much investigation. New problems are confronting both the builders and users of steam and gas motors. There is at present a noteworthy drift from the recip-

rocating engine to the steam turbine. Gas engines of large power have recently been installed, and the development of this type of motor bids fair to be more rapid in the near future. Still newer types of motors are being proposed from time to time, the gas turbine being one that at present occupies much attention as an attractive possibility.

It is evident that the Experiment Station may be of considerable service in this line of work. For the user of power, it can investigate questions relative to the economy of various types of power installations with given conditions of service. For the builder of motors it can investigate the new and perplexing problems that have arisen. The properties of the various fluids used in heat motors need careful study. Superheated steam is essential to the proper working of a steam turbine, yet little is known of its properties. The properties of ammonia and other fluids used in refrigeration are not known accurately, and even the properties of saturated steam are based on Regnault's experiments made nearly seventy years ago. A careful investigation of the properties of heat media of all kinds, extending if necessary over a series of years, would furnish data of the greatest value to engineers, and would in addition be a noteworthy contribution to science.

Railroads.—Considerable work for the railroad interests has already been done by the railway mechanical engineering department of the University. The dynamometer car owned jointly by this department and the Illinois Central Railroad has been used in numerous road tests, and these tests have been used as a basis for the computation of tonnage ratings. This work will be prosecuted vigorously under the direction of the new department of railway engineering and administration recently organized.

Other problems relating to design, maintenance of way, etc., will be attacked as they arise. The question of electric traction is becoming one of great importance in Illinois. The electrical engineering department has recently added to its equipment a new dynamometer car, with which tests may be made on electric lines, and it is expected that these tests will furnish valuable data.

Manufacturing and Building.—It is expected that the Experiment Station will prove helpful to the manufacturing and building interests of Illinois in several ways. In the first place, it will supply accurate data regarding the properties of the materials used in engineering structures and buildings. The new lab-

oratory of applied mechanics with its extensive equipment furnishes ample facilities for this line of work. The new 600,000-pound vertical testing machine permits the testing of full-sized specimens 24 feet in length. The reinforced concrete tests now in progress show the possibilities in this line of work. In the near future, an extensive series of tests on cast-iron columns, and others on steel plates are contemplated. A considerable portion of the available funds of the station will be expended in this work of testing materials. Secondly, the Experiment Station will investigate manufacturing processes. As an example of this line of work, the high-speed steel tests are cited. Thirdly, problems relating to design and construction will be studied, and all useful results will be published for the benefit of those engaged in design or construction.

As a rule the Experiment Station will undertake only such investigations as will lead to results of fundamental importance, results that will be helpful to a large class of engineers or manufacturers. It will not, in general, undertake work of importance to individuals only, e. g., the testing of a device or invention for the sole benefit of the inventor.

Those in charge of the Engineering Experiment Station feel that if the work of the station be carried out along the lines here suggested, and if proper support be afforded by the state in order that the work can be so carried out, the engineering industries of Illinois will receive benefits which will amply repay all expenditures.

VIII. Cooperation

It is very essential that great care should be exercised in the selection of subjects to be investigated. It is equally important that the results of the investigations should be published in such shape as will best serve the purposes of engineers and manufacturers. In order that these ends may be attained it has been thought desirable that there shall be organized several committees of conference on matters of widespread interest. One such committee has already been appointed, the Conference Committee on Fuel Tests, composed of representatives appointed by the following Illinois organizations: State Geological Survey, Western Society of Engineers, Building Managers' Association of Chicago, Western Railway Club, Illinois Manufacturers' Association, Illinois Coal Operators' Association, State Electric Light Association,

Board of Trustees University of Illinois, and the State Engineering Experiment Station. It is planned to form similar committees relating to other lines of work whenever the importance of the investigations warrants it. It is hoped that suggestions may be proposed to the station from engineers, or from mining, railway, or manufacturing interests, to the end that the work of the station may grow to be of real value to the commercial interests of the state. Engineering societies will find at the University excellent facilities for meeting, and it is suggested that such societies plan to hold their meetings here as often as possible.

The desirability of cooperating with similar state experiment stations or with some of the national departments having charge of tests of fuel, timbers, structural materials, or with water surveys, etc., is also evident, and such cooperation will be sought whenever mutual good is promised. Such a method will often tend to concentrate isolated and scattered efforts, and will also tend to standardize methods of tests and forms of reports and specifications.

Publications Of The Engineering Experiment Station

Bulletin No. 1. Tests of Reinforced Concrete Beams, by A. N. Talbot. 1904.

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 5 JUNE 1906

RESISTANCE OF TUBES TO COLLAPSE

BY ALBERT P. CARMAN, PROFESSOR OF PHYSICS
AND
MAURICE L. CARR, ASSISTANT IN PHYSICS

This paper describes a series of experiments made on the resistance of metal tubes to collapse when subjected to external hydraulic pressure. The principal use of the results of such experiments is probably their application to the design and inspection of the fire flues of steam boilers, but the results are also of great interest and importance in the theory of elasticity and the strength of materials. Engineers have used various empirical rules and formulæ for the collapse of tubes, but these formulæ have been derived from a few unsatisfactory experiments and have within recent years been generally distrusted. This distrust has not been lessened by the mathematical discussions of the last few years, in which students of elasticity have attempted to derive a rational formula for tube collapses. These proposed rational formulæ differ, as we shall see, from the empirical rules in use by engineers.

The present work was first planned by L. P. Breckenridge and A. P. Carman in the spring of 1904, but University duties prevented its prosecution at that time. In the winter of 1904 to 1905, a series of experiments on the collapse of small seamless brass tubes was carried out by A. P. Carman. These experiments were described and the results discussed in a paper read before the American Physical Society at Chicago, April 23, 1905, and published later in the Physical Review.[1] It was there shown that the form-

[1] A. P. Carman, Collapse of Tubes, Physical Review, Vol. XXI, pp. 381-387.

ulæ in general use, all of which are based on that of Sir William Fairbairn, are inadequate; that there is a certain "critical minimum length" beyond which the resistance to collapse of a tube is independent of the length; and that a formula of the rational type proposed by Professor G. H. Bryan was probably nearly true for these small brass tubes.

The experiments discussed in this bulletin have been made by the department of Physics of the Engineering Experiment Station of the University of Illinois. They were begun in the fall of 1905, but owing to delays in getting apparatus and materials were not completed until May 1, 1906. M. L. Carr, B. S., has been the assistant in carrying on this series of experiments. He has made the observations, and to him are due several of the special devices used as well as much of the completeness and accuracy of the calculations. Before describing our own experiments and discussing the results, we shall give a brief account of previous experiments and of the empirical and theoretical formulæ which have been proposed.

Historical

The first and until very recently the only systematic experiments on the collapse of tubes were those of Sir William Fairbairn made nearly fifty years ago[1]. Fairbairn's work was done at the suggestion and with the aid of the Royal Society and of the British Association for the Advancement of Science. The common steam pressure in that day was 50 pounds per square inch or less, and so the highest pressure thought necessary by Fairbairn was less than 500 pounds. The tubes were "composed of a single thin iron plate bent to the required form upon a mandril and riveted and also brazed to prevent leakage into the interior". The ends were closed by cast-iron disks or plugs, and the tube was placed in a large cast-iron cylinder and there subjected to hydraulic pressure. Fig. 1 is reproduced from Fairbairn's original paper and shows his arrangement. The cast-iron cylinder was 8 feet long, 28 inches in diameter and the walls were 2 inches thick. The cylinder was placed in a vertical position and the tube was

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[1] William Fairbairn. On the Resistance of Tubes to Collapse. Philosophical Transactions of the Royal Society of London for 1858, pp. 389-413; also in Fairbairn's Useful Information for Engineers. Second Series. London, 1867.

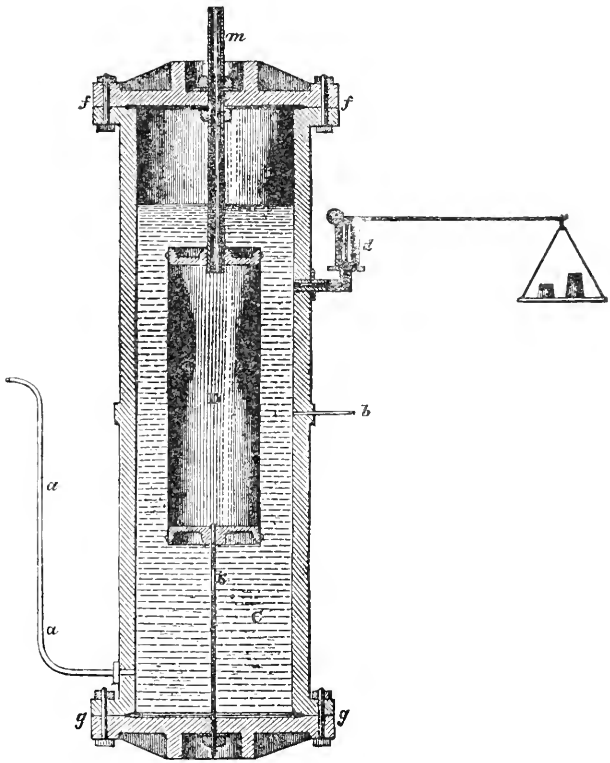

FIG. 1 SIR WM. FAIRBAIRN'S APPARATUS FOR TESTING TUBES, REPRODUCED FROM PHIL. TRANS. FOR 1858

supported from both ends, as shown in the figure. The interior of the tested tube was connected with the atmosphere at the upper end. The pressure was produced by a hydraulic pump and was read by steam gauges. A safety valve set at 500 pounds limited the pressure. The diameters of the tubes collapsed were 4, 6, 8, 9, 10 and 12 inches with the exception of one which was $18\frac{3}{4}$ inches in diameter. The length of these tubes ranged from 19 to 60 inches, and nearly all had the same wall thickness of .043 of an inch. In all, about twenty-five satisfactory collapses were made. Fairbairn sums up his results in this well-known formula:

$$P = 9{,}675{,}600 \frac{t^{2.19}}{l\,d}$$

"Which is", he says, "the general formula for calculating the strength of wrought-iron tubes subjected to the external pressure within the limits indicated by the experiments; i. e., provided their length is not less than 1.5 feet, and not greater than 10 feet". In the above formula, P = pressure in pounds per square inch; t = thickness of wall in inches; l = length of tube in inches; and d = diameter in inches. Fairbairn adds as a foot-note the following: "By taking 2 instead of 2.19 for the index of t, this formula becomes

$$P = 9{,}675{,}600 \frac{t^2}{ld}$$

whence the value of P may be calculated by ordinary arithmetic. For thick tubes of considerable diameter and length, this formula may be regarded as sufficiently exact for practical purposes". This last or approximate form is sometimes known as Fairbairn's second form. Fairbairn's formula has been the text for practically all the discussions on the collapse of tubes for the last fifty years. Aside from Fairbairn's experiments, there have been no systematic experiments described until within the last year. It is noteworthy that a problem so widely discussed, the solution of which has not only great scientific interest but also valuable technical applications, should remain for so many years with so little experimental work. The only reasons that can be assigned are the considerable expense involved in the experiments and the fact that the appliances needed are not commonly available in testing laboratories.

TABLE I

FAIRBAIRN'S DATA ON THE RESISTANCE OF TUBES TO COLLAPSE

Diameter, inches	Length, incehs	Thicknes of Wall, inches	Pressure of Collapse, lb. per sq. in.	Remarks
4	19	.043	170	Tubes formed of plates of uniform thickness.
4	19	.043	137	Tubes formed of plates of uniform thickness.
4	40	.043	65	Tubes formed of plates of uniform thickness.
4	38	.043	65	Tubes formed of plates of uniform thickness.
4	60	.043	43	Tubes formed of plates of uniform thickness.
4	60	.043	140	Made in 3 sections, 1 ft. 7 in. each.
4	60	.043	47	
4	30	.043	(195)	Ends of tube fractured, allowing water to enter and cause reacting pressure.
4	30	.043	93	
4	15	.043	147	
6	30	.043	48	Cast-iron ends fractured, causing collapse before outer shell attained maximum resistance.
6	29	.043	47	
6	59	.043	32	
6	30	.043	52	
6	30	.043	65	
6	30	.043	85	Rod placed down axis to prevent end from approaching. Tin ring left in caused increased pressure.
8	30	.043	39	
8	39	.043	32	
8	40	.043	31	
8	60	.043	22	
8	30	.043	36	
10	50	.043	19	
10	30	.043	33	
12	30	.043	22	
12	60	.043	12.5	
12.2	58.5	.043	11	
9	37	.25	(450)	Uncollapsed.
18.75	61	.25	420	
9	37	.14	262	Lap joint.
9	37	.14	378	Butt joint.
14x10.25	60	.043	6.5	Elliptical tubes.
20.75x15.5	61	.25	127.5	Elliptical tubes.

The most remarkable feature of Fairbairn's formula is the dependence of the collapsing pressure upon the length. This will be discussed later. Immediately after the publication of Fairbairn's paper, one writer after another began to discuss the data for the purpose of deducing a more general and convenient empirical formula. The following is a partial list of the best known of such formulæ. The dimensions are given in inches just as in the form of Fairbairn's formula:

(1) By F. Grashof: in Zeitschrift des Vereines deutscher Ingenieure, p. 234, 1859.

(a) For thick tubes:

$$P = 1{,}033{,}620 \frac{t^{2.081}}{l^{0.564} d^{0.889}}$$

(b) For thin tubes:

$$P = 24{,}481{,}000 \frac{t^{2.315}}{l d^{1.278}}$$

(2) By G. H. Love: in Todhunter and Pearson's History of Elasticity, Vol. II, p. 667. Appeared in Civilingenieur, 1861.

$$P = 5{,}358{,}150 \frac{t^2}{ld} + 41906 \frac{t^2}{d} + 1323 \frac{t}{d}$$

(3) By J. W. Nystrom: Quoted here from Van Nostrand's Engineering Magazine, Vol. XXIV, p. 213. Original reference, Treatise on Steam Engineering, by J. W. Nystrom, p. 106.

$$P = 692{,}800 \frac{t^2}{l^{0.5} d}$$

(4) By W. C. Unwin: in Minutes of Proceedings of Institution of Civil Engineers, Session 1875–1876, Part IV, p. 225.

$$P = 15{,}547{,}000 \frac{t^{2.35}}{l^{0.9} d^{1.16}}$$

for flues with longitudinal and circumferential joints.

(5) By F. Wehage: in Dingler's Polytechnisches Journal, pp. 236–243, 1881.

$$P = \left\{ \begin{matrix} 368{,}000 \\ 490{,}000 \end{matrix} \right. \frac{8t}{d} \cdot \sqrt[3]{\frac{t}{ld}}$$

The coefficient 368,000 to be used for flues with lap joints riveted; the 490,000 to be used for flues with flap joints riveted on.

(6) By Theodore Belpaire: Note sur la résistance des tubes pressées de l'extérieur, par Theodore Belpaire in Annales du Génie civil, March, 1879. Quoted from Van Nostrand's Magazine, Vol. XXIV, 1881.

$$P = 3{,}427{,}152 \left[\frac{t^2}{ld} \right] - 56{,}892{,}400 \left[\frac{t^3}{ld^2} \right]$$

All of the above formulæ have the same fundamental form as Fairbairn's. Indeed, we might expect this, for they are simply

empirical expressions made to fit Fairbairn's observations. Most writers had seen that there must be a limit to the length of tubes for which these formulæ should be applied, but no results of experiments had been published previous to 1905 regarding this.

The previous experiments by the writer were made to test this principal characteristic of the Fairbairn formula, viz., that the collapsing pressure varies inversely as the length. Twenty-five small seamless brass tubes were collapsed by hydraulic pressure. The diameter, thickness of wall, length and collapsing pressure are shown in the following table:

TABLE II

TABLE OF COLLAPSING PRESSURES OF SMALL SEAMLESS BRASS TUBES[1]

Mean Diameter, inches	Thickness of Wall, inches	Length, inches	Collapsing Pressure, lb. per sq. in.
.350	.0163	.315	4125
.350	.0163	.472	3415
.350	.0163	.709	3200
.350	.0163	1.063	2248
.350	.0163	1.570	1778
.350	.0163	3.150	1850
.350	.0163	3.540	1850
.350	.0163	1.570	9525
.441	.0315	2.280	6975
.441	.0315	2.715	6690
.441	.0315	3.345	6690
.441	.0315	3.820	6400
.441	.0315	7.480	6690
.721	.0315	1.220	7750
.721	.0315	1.733	6620
.721	.0315	2.280	6260
.721	.0315	3.030	5120
.721	.0315	8.200	4980
.721	.0315	3.420	11940
.701	.0531	3.500	12200
.701	.0531	5.120	12090
.701	.0531	5.120	12020
.701	.0531	5.190	11940
.701	.0531	5.270	12090
.701	.0531	8.270	12090

The curve, Fig. 2, shows the relation between length and collapsing pressure for tubes 0.35 of an inch in diameter. The curves for the other diameters are of the same shape. The following conclusions were drawn. "An inspection of these data and curves shows immediately that there is a minimum length for

[1] Data taken by Professor A. P. Carman, from Physical Review, Vol. XXI, No. 6, Dec., 1905.

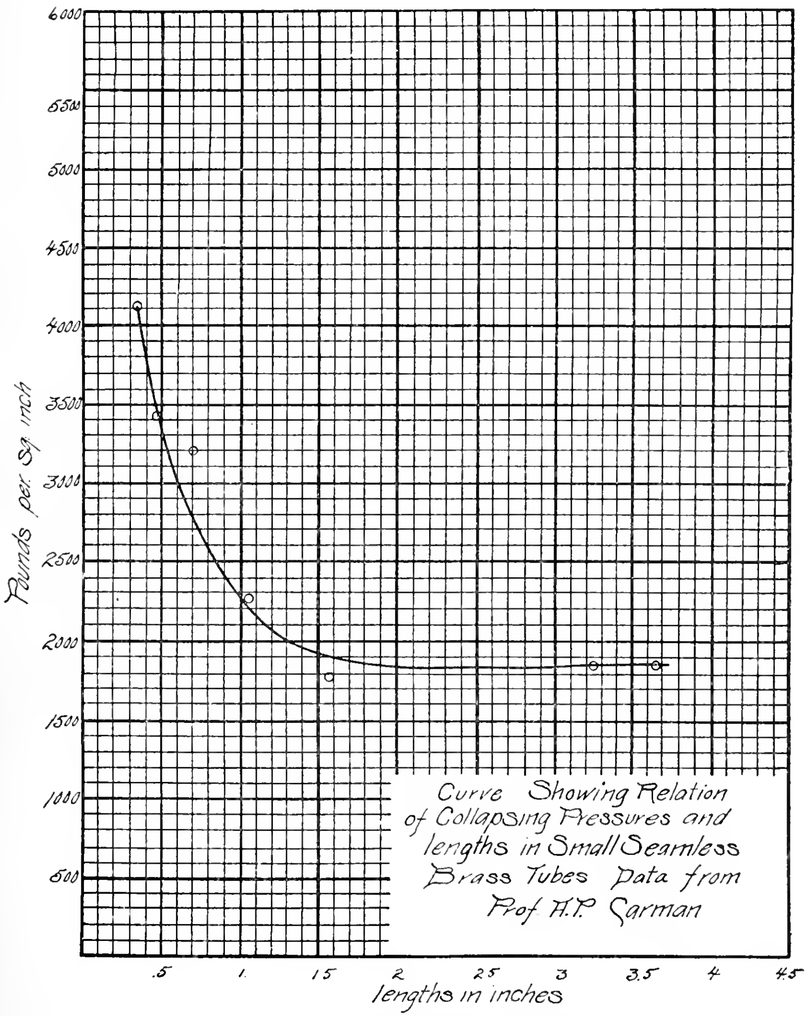

FIG. 2 CURVE SHOWING RELATION OF COLLAPSING PRESSURE TO LENGTH IN SMALL SEAMLESS BRASS TUBES

each tube beyond which the collapsing pressure is constant; and further, that this minimum length is quite definite. Again, we see that for lengths less than this critical minimum length, the collapsing pressures rise rapidly. As definitely as can be determined from these small tubes, the collapsing pressure varies inversely as the length, for lengths less than the critical length. In this they follow Fairbairn's formula, and suggest that Fairbairn's tubes were all shorter than their critical lengths. An inspection of the woodcuts which Fairbairn gives for each of his experiments, and a comparison of these with the shapes of the brass tubes which have been collapsed in our experiments confirm this. Figs. 3 and 4 show shapes and sections of the collapsed tubes of the curve, Fig. 2. Fairbairn found exactly these shapes which we have obtained for lengths less than the critical length".[1]

These previous experiments had thus shown the inadequacy of Fairbairn's formula, and they had particularly shown the very narrow range of the law of inverse lengths. When the present series of experiments on standard steel boiler flues was begun, little attention was therefore paid to the law of lengths, except to see that the tubes were longer than the critical minimum length.

Methods and Data of Experiments

The method followed in the present tests was similar to that used by Fairbairn. The tube to be tested was closed at both ends, placed inside a stout steel cylinder, and there subjected to increasing external water pressure until the tube collapsed. The pressures were read by hydraulic gauges. The cylinder used in all these experiments was a section of a nickel steel naval gun tube, kindly furnished at a nominal price by the Bethlehem Steel Company, Bethlehem, Pennsylvania. The dimensions of this gun tube were: length, 12 feet; external diameter, 7 inches; internal diameter, 5 inches. For a distance of six inches at one end, the external diameter was left at 9 inches, thus making a shoulder against which the end plug could be clamped. This plug was a steel disk with a projection, and was held in place by heavy cast-iron rings and eight $1\frac{1}{4}$-inch steel bolts. A lead gasket with circular grooves in the end face of the tube prevented leakage even at the highest pressures. The other end of the nickel steel cylinder was closed by a cast-iron plug, six inches long, shrunk into place.

[1] A. P. Carman. Am. Physical Society, April, 1905.

A ¾-inch hole for stay rods was drilled through the center of each end plug. Leakage about the rods was prevented by packing held in place by bushing nuts. These stay rods were made of ¾-inch steel shafting, and were screwed, one into each end plug of the tube to be tested. The tube could thus be put under tension so as to take up the end pressures. One of these stay rods had a small hole through it connecting the interior of the tube with the atmosphere. By rubber tubing, the interior could be connected with a U manometer. This manometer was very useful in indicating any leakage.

In the first experiments, the tube to be tested was closed by steel plugs, fitted and soldered in the ends. Experience soon showed that soldering the plugs was both a tedious and an uncertain method of closing the ends. Several other plans were tried before a satisfactory and convenient method was found. The final method is shown in Fig. 5. Tool-steel clamps were made in the shape of split rings, hinged on one side and held together on the other side by bolts. These ring clamps were placed on the tube near the end as a grip, and slipping was prevented by burring the tube with a cold chisel. A steel disk faced with a sheet of lead was then drawn tight against the plane ends of the tube by bolts screwing into the clamps. After the ends were clamped on the tube it could be tested for leakage by placing the whole tube in a trough of water, and pumping air into it with a foot bicycle pump through the bored stay rod. It was seldom that a tube tested in this way leaked when subjected even to high external water pressure. The connections with the gauges, the pump and the hydrant were made through small holes bored in the nickel steel cylinder. These holes were made tight by special screw plugs and leather gaskets. The cylinder was mounted on two heavy trestles and inclined so as to allow the easy escape of the air when filling it with water. The pressures were produced by a Cailletet pump made by the Societé Genevoise, of Geneva, Switzerland. The pump was capable of producing pressures of 1000 kilograms per square centimeter, or approximately 14,000 pounds per square inch. Copper pressure tubing was used to connect the pump and the gauges with the cylinder. Four gauges made by Shæffer and Budenberg were used, viz.:

No. 1, reading to 8000 pounds per square inch.

No. 2, reading to 1000 kilograms per square centimeter.

No. 3, reading to 3000 pounds per square inch.

No. 4, reading to 300 kilograms per square centimeter.

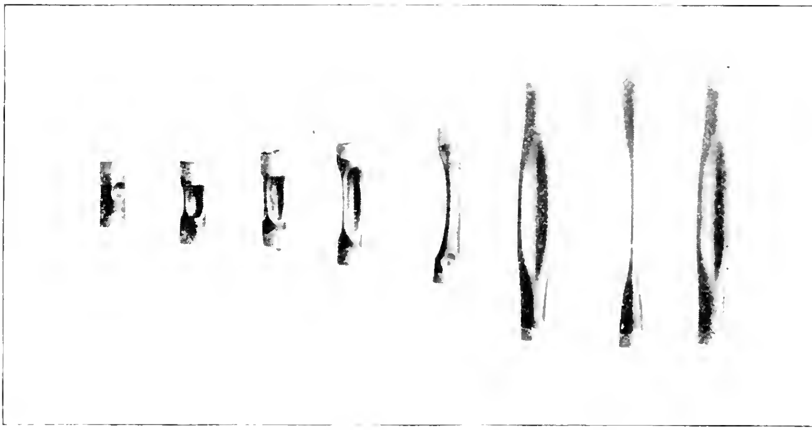

Fig. 3 Appearance of Collapsed Small Seamless Brass Tubes

Referred to in Figs. 2 and 4

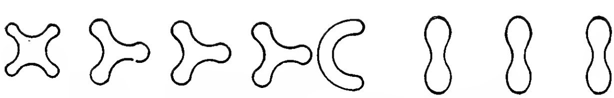

Fig. 4 Sections of Collapsed Small Seamless Brass Tubes

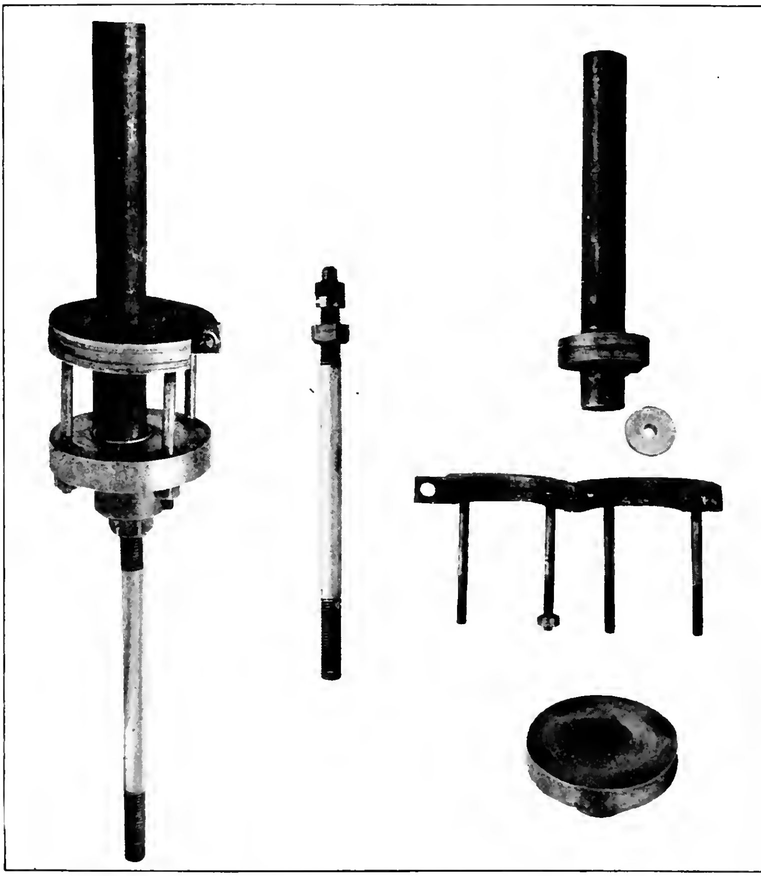

FIG. 5 PARTS OF CLAMP FOR STOPPING END OF TUBE
(on the right)
CLAMP IN PLACE ON TUBE
(on the left)

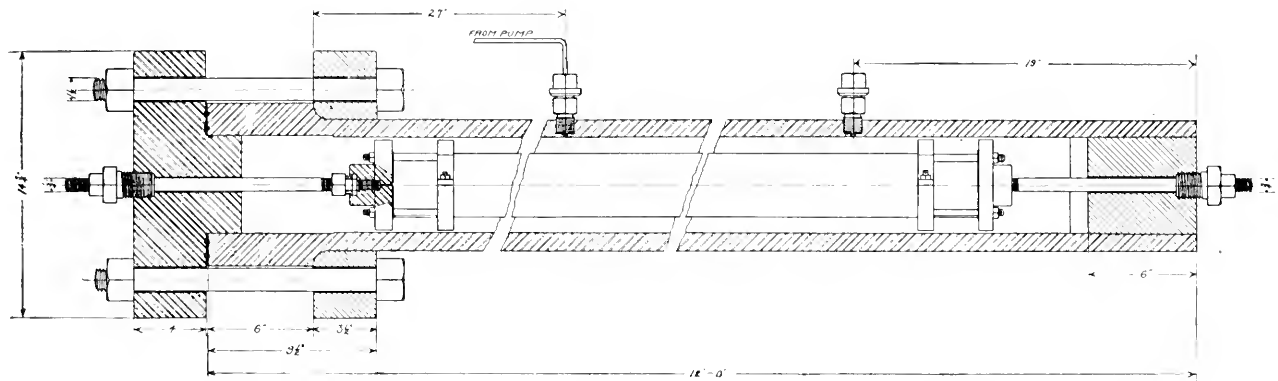

Fig. 6 Section of Nickel Steel Cylinder, with Tube to be Tested in Place, Showing End Plugs and Connection to Pump

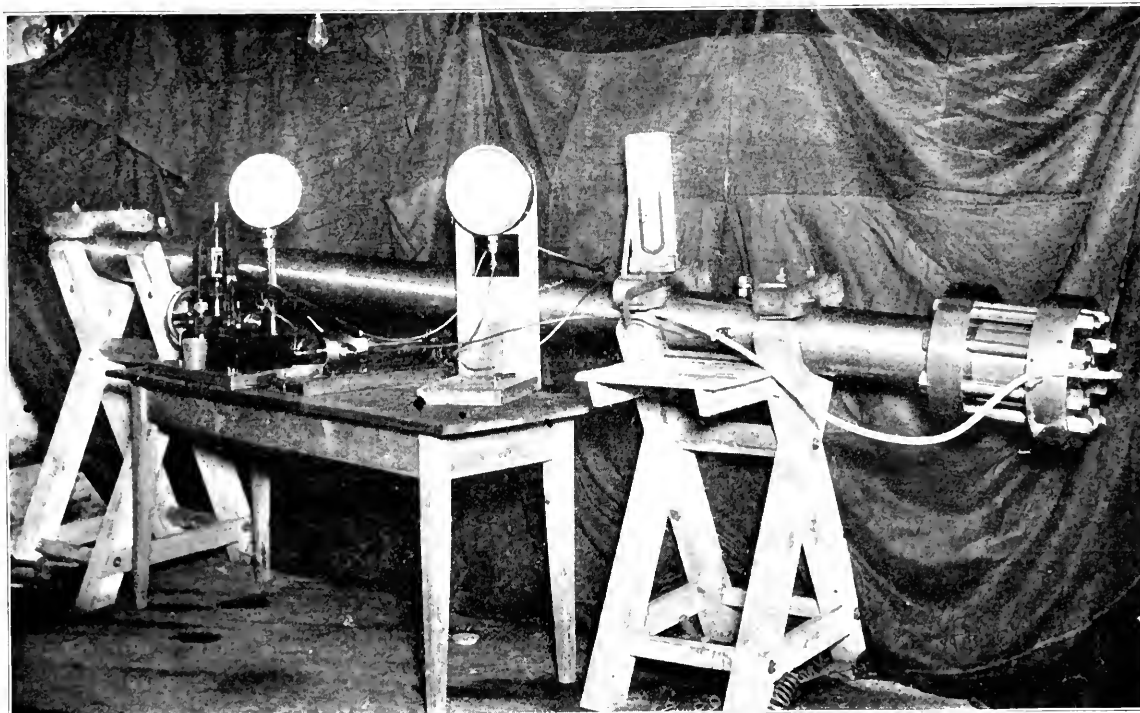

Fig. 7 Apparatus For Collapsing Tubes

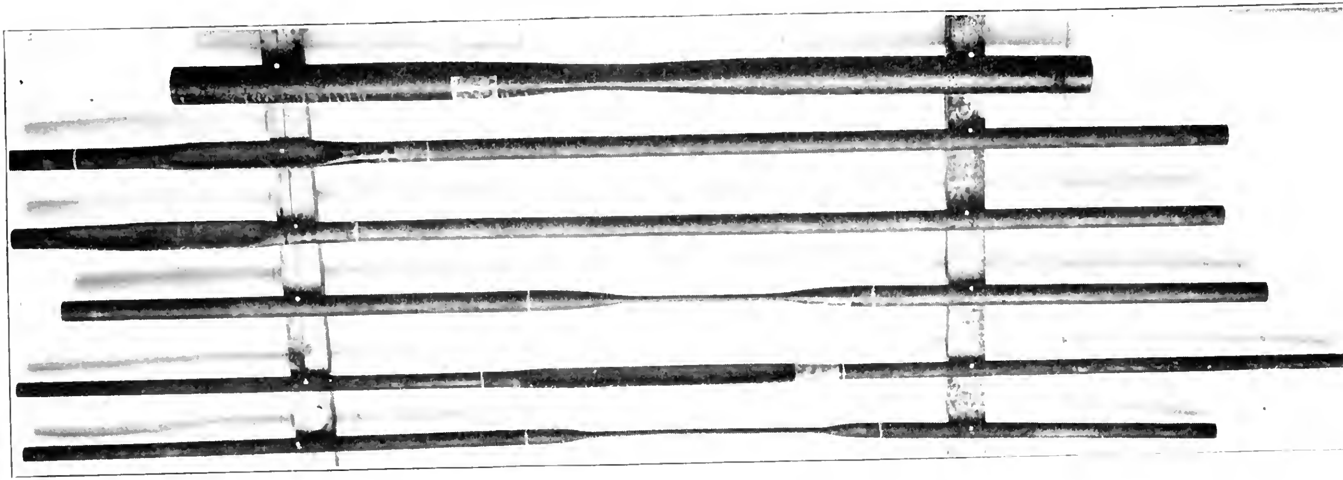

Fig. 8 Tubes Which Have Been Collapsed, Showing Shape of Collapse

Fig. 9 Tube with End Stopped and with Stay Rods, Ready to be Put into Cylinder for Test

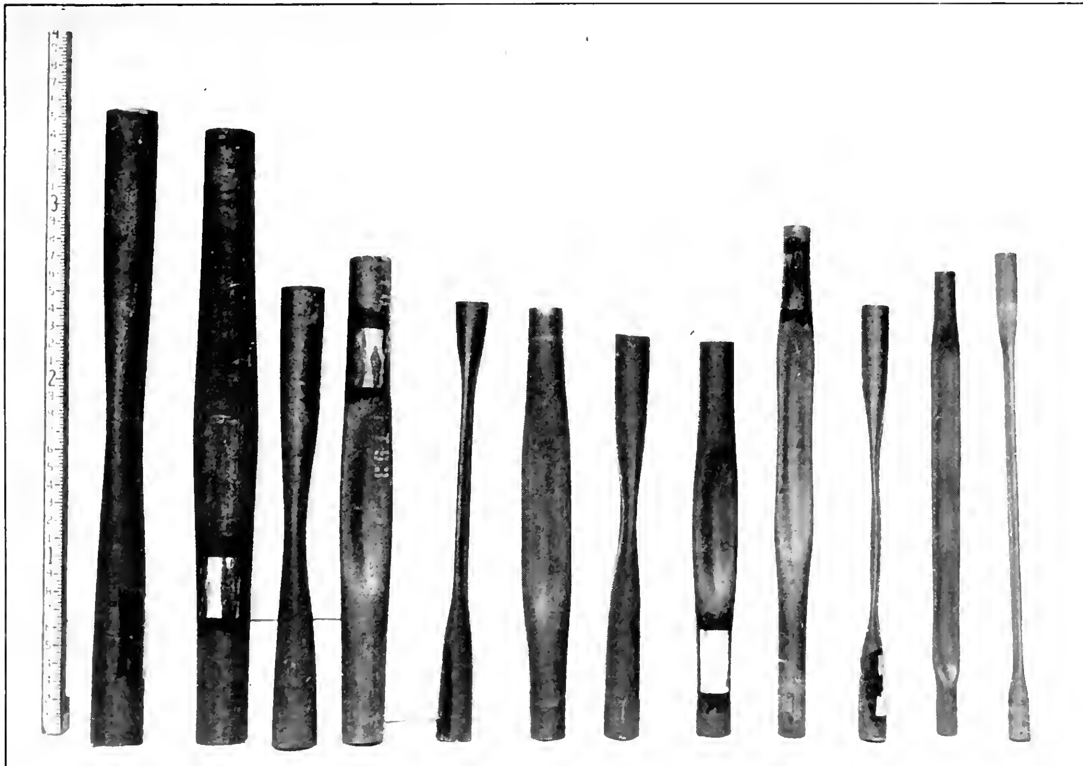

FIG. 10 COLLAPSED PORTIONS OF SOME BOILER TUBES

Gauges Nos. 1 and 3 had maximum pointers, and all had check valves to protect the springs from the shock at collapse. The drawing of the cylinder, Fig. 6 and the photograph, Fig. 7, of the assembled apparatus show other features not easily described.

When a test was to be made, the prepared tube was placed in the cylinder, the heavy head bolted on, and the cylinder filled with water from the hydrant. All the openings were then closed, and the pressure pump started. Several minutes of pumping were usually required before the gauges began to record. Except for a few thin tubes of large diameter, failure, which was sudden in all cases, was accompanied by a sound much like that accompanying the failure of a specimen in a testing machine. Failure was also indicated by the dropping of the gauges and the rise of the water in the manometer connected with the inside of the tube. Each specimen was carefully measured after collapse, and in the case of most of the tested tubes, the collapsed portion was sawed across and the actual average thickness of the tube was obtained. Nearly all of the tubes tested were ten feet long at the start. In many cases, three or more collapses were made by cutting off the collapsed portion after each failure, and then testing the remainder of the tube. In the tables of data, these are noted as sections of the flue, e. g., flue No. 1 was divided into three sections, 1, 2 and 3. The tubes tested were commercial steel boiler tubes, both lap-welded and cold drawn seamless. We have to thank J. T. Ryerson and Son, Chicago, for the gift of four tubes, and the Scully Steel and Iron Company, Chicago, for the gift of twenty-five tubes for these tests. The other tubes used were bought in the open market. In order to have data on entirely different material, tests were made on a set of brass tubes similar in size to the steel tubes. The advantage of the brass tube tests was that the dimensions and the material were much more uniform.

CHEMICAL TESTS OF SAMPLES OF BOILER FLUES COLLAPSED

Description of Sample of Flue	CHEMICAL ANALYSIS				
	Si	S	P	Mn	C
Lap-welded steel..............	....	.021	.137	.286	.080
Lap-welded steel..............	....	.038	.099	.330	.080
Seamless cold drawn steel.....	....	.001	.018	.462	.170
Seamless cold drawn steel....	....	.002	.013	.525	.220

TABLE III

DATA ON SEAMLESS COLD DRAWN FLUES

Flue No.	Flue Sec.	Length	Diameter, inches	Nominal Thickness, inches	Actual Av. Thickness, inches	Collapsing Pressure, lb. per sq. in.	Length of Collapse, inches	Distance of Collapse from Vented End
25	......	9 ft. 6 in.	1.5	.095	.097	4220	32	5 ft. 2 in.
26	1	9 ft. 7 in.	1.5	.095	.098	4260	30	8 ft. 2 in.
26	2	6 ft. 11 in.	1.5	.095	......	4260	38	5 ft. 6 in.
26	3	2 ft. 8 in.	1.5	.095	......	3930	25	1 ft. 6 in.
27	......	9 ft. 7 in.	1.5	.095	......	5200	3	At extreme end of flue.
28	......	8 ft. 4 in.	1.5	.095	.100	4330	32	4 ft. 6 in.
29	......	8 ft. 4 in.	1.5	.095	.102	4240	29	1 ft. 4 in.
45	......	9 ft. 2 in.	1.5	.095	.095	3930	29	6 ft. 4 in.
Mean	......	....	......	......	.098	4200	30.4	....
42	......	9 ft. 7 in.	2	.095	.102	3050	27	1 ft. 0 in.
43	......	9 ft. 7 in.	2	......	.092	2420	20	6 ft. 4 in.
44	......	9 ft. 7 in.	2	......	.103	3390	36	6 ft. 4 in.
Mean	......	....	......	......	.099	2950	28	....
36	......	9 ft. 8 in.	2.5	.083	.084	1280	27	5 ft. 0 in.
37	......	9 ft. 7 in.	2.5	.083	.084	1100	26	6 ft. 8 in.
Mean	......	....	......	......	.084	1190	26.5	....
39	......	9 ft. 7 in.	2.5	.095	.103	1820	35	....
40	......	9 ft. 6 in.	2.5	.095	.098	1730	27	4 ft. 6 in.
41	......	9 ft. 7 in.	2.5	.095	.098	1890	22	9 ft. 0 in.
Mean	......	....	......	......	.099	1810	28	....
3	1	10 ft. 0 in.	2.5	.109	.114	1720	28	1 ft. 2 in.
3	2	6 ft. 10 in.	2.5	.109	......	1920	27	2 ft. 2 in.
3	3	3 ft. 4 in.	2.5	.109	......	2200	24	1 ft. 10 in.
4	1	9 ft. 8 in.	2.5	.109	.116	1980	25	....
4	2	5 ft. 10 in.	2.5	.109	......	2470	27	2 ft. 3 in.
4	3	....	2.5	.109	......	2610	......	....
38	......	9 ft. 7 in.	2.5	.109	.109	1580	25	1 ft. 9 in.
Mean	......	....	......	......	.113	1960	27	....
1	1	9 ft. 0 in.	2.5	.120	.120	1830	27	....
1	2	4 ft. 11 in.	2.5	.120	......	1850	26	....
1	3	1 ft. 9 in.	2.5	.120	......	2190	21	....
2	1	7 ft. 9 in.	2.5	.120	.121	2320	28	5 ft. 6 in.
2	2	3 ft. 6 in.	2.5	.120	......	2650	23	1 ft. 9 in.
Mean	......	....	......	......	.120	2070	25	....
33	......	9 ft. 7 in.	3	.095	.094	1190	28	4 ft. 0 in.
34	......	9 ft. 7 in.	3	.095	.102	1160	33	8 ft. 0 in.
35	......	9 ft. 7 in.	3	.095	.097	1130	32	8 ft. 0 in.
Mean	......	....	......	......	.098	1160	31	....
30	......	9 ft. 7 in.	3.5	.095	.093	990	37	6 ft. 0 in.
31	......	9 ft. 7 in.	3.5	.095	.096	900	55	7 ft. 0 in.
32	......	9 ft. 7 in.	3.5	.095	.093	970	42	6 ft. 7 in.
Mean	......	....	......	......	.094	950	45	....

TABLE IV

DATA ON LAP-WELDED STEEL BOILER FLUES

Flue No.	Flue Sec.	Length	Diameter, inches	Nominal Thickness, inches	Actual Av. Thickness, inches	Collapsing Pressure, lb. per sq. in.	Length of Collapse, inches	Distance of Collapse from Vented End
5	1	8 ft. 10 in.	2.5	.109	.114	2850	29	....
5	2	5 ft. 10 in.	2.5	.109	......	3040	31	....
5	3	3 ft. 0 in.	2.5	.109	......	3400	29	1 ft. 1 in.
6	1	8 ft. 8 in.	2.5	.109	.116	2810	......	....
6	2	6 ft. 0 in.	2.5	.109	......	2930	27	4 ft. 11 in.
6	3	3 ft. 7 in.	2.5	.109	......	3080	21	0 ft. 7 in.
7	1	8 ft. 8 in.	2.5	.109	.120	2700	37	....
7	2	2 ft. 4 in.	2.5	.109	......	2850	27	1 ft. 1 in.
8	1	9 ft. 0 in.	2.5	.109	.112	2900	25	4 ft. 6 in.
8	2	3 ft. 3 in.	2.5	.109	......	2950	25	2 ft. 0 in.
8	3	2 ft. 6 in.	2.5	.109	......	3170	24	1 ft. 6 in.
9	1	9 ft. 0 in.	2.5	.109	.120	3160	20	....
9	2	5 ft. 10 in.	2.5	.109	......	3450	27	3 ft. 1 in.
10	1	9 ft. 0 in.	3	.109	.105	2080	30	1 ft. 9 in.
10	2	4 ft. 11 in.	3	.109	......	2150	29	3 ft. 5 in.
10	3	2 ft. 10 in.	3	.109	......	2350	29	0 ft. 8 in.
11	1	9 ft. 0 in.	3	.109	.111	2190	23	8 ft. 6 in.
11	2	6 ft. 6 in.	3	.109	......	2430	30	1 ft. 7 in.
11	3	3 ft. 8 in.	3	.109	......	2620	26	2 ft. 6 in.
11	4	1 ft. 8 in.	3	.109	......	3150	20	0 ft. 10 in.
12	1	9 ft. 0 in.	3	.109	.105	1910	4	At extreme end of flue.
12	2	8 ft. 8 in.	3	.109	......	2020	27	7 ft. 6 in.
12	3	5 ft. 1 in.	3	.109	......	1960	30	1 ft. 4 in.
12	4	2 ft. 6 in.	3	.109	......	1920	26	1 ft. 9 in.
13	1	9 ft. 0 in.	3	.109	.106	2140	32	6 ft. 8 in.
13	2	5 ft. 1 in.	3	.109	......	2220	33	2 ft. 10 in.
14	1	9 ft. 0 in.	3	.109	.113	2080	32	4 ft. 3 in.
14	2	2 ft. 11 in.	3	.109	......	2000	27	1 ft. 9 in.
14	3	2 ft. 6 in.	3	.109	......	2230	28	1 ft. 2 in.
15	1	9 ft. 5 in.	3.5	.120	.124	1940	31	1 ft. 4 in.
15	2	6 ft. 8 in.	3.5	.120	......	2310	30	1 ft. 2 in.
15	3	4 ft. 1 in.	3.5	.120	......	2470	30	2 ft. 11 in.
15	4	1 ft. 4 in.	3.5	.120	......	2800	16	0 ft. 8 in.
16	1	9 ft. 6 in.	3.5	.120	.129	2180	31	1 ft. 1 in.
16	2	6 ft. 9 in.	3.5	.120	......	2500	30	5 ft. 7 in.
16	3	4 ft. 1 in.	3.5	.120	......	2790	27	2 ft. 11 in.
17	1	9 ft. 8 in.	3.5	.120	.129	2150	41	....
17	2	6 ft. 8 in.	3.5	.120	......	2240	36	1 ft. 5 in.
17	3	3 ft. 4 in.	3.5	.120	......	2660	36	2 ft. 0 in.
18	1	9 ft. 4 in.	3.5	.120	.128	1890	39	....
18	2	6 ft. 4 in.	3.5	.120	......	1870	......	....
19	1	9 ft. 4 in.	3.5	.120	.127	2200	32	1 ft. 4 in.
19	2	6 ft. 8 in.	3.5	.120	.....	2290	42	4 ft. 4 in.
19	3	2 ft. 6 in.	3.5	.120	......	2440	30	1 ft. 2 in.
20	1	8 ft. 5 in.	2	.095	.095	3100	33	7 ft. 2 in.
20	2	5 ft. 5 in.	2	.095	......	3410	29	3 ft. 2 in.
20	3	2 ft. 3 in.	2	.095	......	3640	27	1 ft. 1 in.
21	......	8 ft. 4 in.	2	.095	.098	2650	32	6 ft. 7 in.
22	1	8 ft. 2 in.	2	.095	.106	3180	30	6 ft. 6 in.
22	2	5 ft. 8 in.	2	.095	......	3500	32	4 ft. 1 in.

TABLE IV—*Concluded*

Flue No.	Flue Sec.	Length	Diameter, inches	Nominal Thickness, inches	Actual Av. Thickness, inches	Collapsing Pressure, lb. per sq. in.	Length of Collapse, inches	Distance of Collapse from Vented End
22	3	2 ft. 8 in.	2	.095	......	3700	26	1 ft. 1 in.
23	1	8 ft. 4 in.	2	.095	.102	3260	28	....
23	2	6 ft. 0 in.	2	.095	......	3960	37	1 ft. 8 in.
23	3	3 ft. 0 in.	2	.095	......	4030	27	2 ft. 0 in.
24	......	8 ft. 5 in.	2	.095	.109	3470	31	4 ft. 2 in.

TABLE V

DATA ON BRASS TUBES

Tube		Length	Diameter, inches	Thickness		Collapsing Pressure, lb. per sq. in.	Length of Collapse, inches
No.	Sec.			Gauge	Inches		
1	1	8 ft. 8 in.	3	14	.083	450	34
1	2	3 ft. 7 in.	3	14	.083	490	24
1	3	1 ft. 9 in.	3	14	.083	555	21
2	1	3 ft. 11 in.	3	14	.083	465	26
2	2	0 ft. 8 in.	3	14	.083	725	8
3	1	8 ft. 7 in.	3	19	.042	75	41.5
4	1	8 ft. 7 in.	2	14	.083	1400	23.5
4	2	5 ft. 11 in.	2	14	.083	1440	22
4	3	2 ft. 7 in.	2	14	.083	1440	21
5	1	2 ft. 3 in.	2	14	.083	1400	23
6	......	6 ft. 6.5 in.	2.5	10	.134	2530	24
7	......	6 ft. 0.0 in.	2	12	.109	2440	27.5
8	......	6 ft. 6.5 in.	2	10	.134	3840	31
9	1	6 ft. 5.5 in.	2	19	.042	275	24.5
9	2	3 ft. 4 in.	2	19	.042	325	20
10	......	5 ft. 6.5 in.	2.5	14	.083	710	23
11	......	4 ft. 7 in.	1.5	14	.083	2600	31

OTHER TESTS AND DATA

The present paper was practically completed when a paper appeared by Professor R. T. Stewart, entitled, "Collapsing Pressures of Bessemer Steel Lap-welded Tubes, Three to Ten Inches in Diameter". This paper was read by Professor Stewart before the American Society of Mechanical Engineers at the Chattanooga meeting, May 1 to 4, 1906, and at the present writing is available only in the advance papers of the meeting. It describes a very complete and valuable investigation made at the McKeesport

Works of the National Tube Company on the lap-welded steel tubes of that company, "the Tube Company generously providing every needful facility for carrying on the research in a most thorough manner". Tests on over five hundred tubes are recorded, so that every advantage of averages is gained. Professor Stewart's tests are certain to play an important part in future discussions of tube collapse on account of the completeness and carefulness of the work. The great number of different facts noted will be invaluable to students, although possibly at first confusing to some readers. The method of experimenting is substantially the same as described in this paper, and also the same as was used by Fairbairn. The ends of the tested tubes were not stayed, and much

TABLE VI

DATA ON LAP-WELDED BESSEMER STEEL TUBES—STEWART[1]

Thickness, inches (t)	Diameter, inches (d)	$\frac{t}{d}$	$\left(\frac{t}{d}\right)^2$	$\left(\frac{t}{d}\right)^3$	Collapsing Pressure, lb. per sq. in.	Source of Data
.194	10.026	.0193	.000372	.00000718	383	Table No. 37
.354	8.673	.0408	.001670	.00006800	2028	Table No. 37
.279	6.987	.0400	.001600	.00006400	2147	Table No. 36
.250	6.677	.0374	.001400	.00005240	1879	Table No. 36
.186	6.024	.0309	.000950	.00002940	1251	Table No. 35
.167	6.028	.0277	.000768	.00002120	928	Table No. 35
.327	4.014	.0815	.006640	.00054000	5560	Table No. 34
.212	4.026	.0527	.002780	.00014600	3170	Table No. 34
.175	4.014	.0436	.001900	.00008300	2280	Table No. 34
.112	2.997	.0374	.001400	.00005240	1860	Table No. 34
.165	10.041	.0164	.000269	.00000440	225	Table No. 30

longer specimens were used, particularly in the first experiments. Most of the experiments were on tubes of larger diameter than ours, Stewart's smaller tubes being indeed the same as our larger tubes. Stewart's experiments are confined to lap-welded tubes, while the tests described in the present paper include also cold drawn seamless steel and brass tubes. The experiments thus supplement each other. Professor Stewart sums up the results of his work as follows: "The principal conclusions to be drawn from the results of the present research may be stated briefly as follows:

(1) The length of tube, between transverse joints tending to hold it to a circular form, has no practical influence upon the

[1] Data taken from a paper read by Professor R. T. Stewart before the American Society of Mechanical Engineers, at Chattanooga, May, 1906. Paper No. 09!.

collapsing pressure of a commercial lap-welded steel tube so long as this length is not less than about six diameters of tube.

(2) The formulæ, as based upon the present research, for the collapsing pressure of modern lap-welded Bessemer steel tubes are as follows:

$$\text{(a)} \quad P = 1{,}000\left(1 - \sqrt{1 - 1600\frac{t^2}{d^2}}\right)$$

$$\text{(b)} \quad P = 86{,}670\frac{t}{d} - 1386$$

Where $P =$ collapsing pressure, pounds per square inch; $d =$ outside diameter of tube in inches; $t =$ thickness of wall in inches.

Formula (a) is for values of P less than 581 pounds, or for values of $\frac{t}{d}$ less than 0.023, while formula (b) is for values greater than these.

(3) The apparent fiber stress under which the different tubes failed, varied from about 7000 pounds for the relatively thinnest to 35,000 pounds per square inch for the relatively thickest walls. Since the average yield point of the material was 37,000 and the tensile strength 58,000 pounds per square inch, it would appear that the strength of a tube subjected to a fluid collapsing pressure is not dependent alone upon either the elastic limit or ultimate strength of the material constituting it".

It will, of course, be impossible to make even an abstract of Professor Stewart's voluminous data, but the substantial agreement of our curves of results with his will be shown in the discussion. A considerable amount of experimental work was done by Professor Stewart in reaching his first conclusion, viz., that the law of inverse lengths did not hold for long tubes. As mentioned above, we had reached this conclusion in experiments described and published before the present experiments were begun.

Rational Formulæ

We turn now to the theoretical discussion of tube collapses. The problem involved is one of unstable equilibrium, and as A. E. H. Love, the author of one of our best theoretical treatises on elasticity, says, belongs to one of the most difficult chapters in the theory of elasticity. Within the last eighteen years, three mathematicians of the University of Cambridge, England, have

discussed the problem of collapse, basing the discussion on the general equations of mechanics and elasticity.

Professor G. H. Bryan[1] seems to have been the first to deduce a formula. Mr. A. B. Basset[2] soon after discussed the subject and proved the same formula in a slightly different form and by other methods. Mr. A. E. H. Love,[3] in his elaborate treatise on elasticity, gives Bryan's formula with a new discussion and with some additions. As stated above, these discussions are all based on the general mathematical equations of elasticity, and are too long and complicated to be presented here. The results, however, have been summed up in excellent form by Love. He says: "Combining the results of this and the previous article, we conclude:

(1) That no flue, however long, can collapse unless the pressure exceed

$$\left\{ \frac{2\,E}{1-\sigma^2} \right\} \frac{h^3}{a^3}$$

(2) That when the pressure exceeds this limit, any flue will collapse if its length exceed a certain multiple of the mean proportional between the diameter and the thickness".

In the above formula, E is the coefficient of elasticity; h is one-half of the thickness; a is the radius of the mean section; and σ is Poisson's ratio. So far as known, no use of this formula has been made in experiments or in engineering practice. It has been developed wholly from the general theory of elasticity, and is distinctly limited by the assumptions, to thin tubes, i. e., where "the thickness $2\,h$ is small compared with the mean radius a".

Previous to this work of the three Cambridge mathematicians, we know of only two published attempts to deduce a rational formula for tube collapses, one by Professor W. C. Unwin and the other by Dr. F. Grashof. Professor Unwin was an assistant of Fairbairn in the original experiments, and nearly twenty years later, in 1876, gave a new discussion of these experiments. He says that the formulæ which have been based on Fairbairn's experiments have no relation to ordinary formulæ of applied me-

[1] G. H. Bryan, Application of the Energy Test to the Collapse of a Long Thin Pipe under External Pressure, Proceedings of the Cambridge Philosophical Society, October 29, 1888, Vol. 6.

[2] A. B. Basset, On the Difficulties of Constructing a Theory of the Collapse of Boiler Flues, Philosophical Magazine, London, 1892, Vol. 200, pp. 221-233.

[3] A. E. H. Love, Mathematical Theory of Elasticity, Cambridge, 1903, Vol. II, pp. 308-316.

chanics, and notes the advantages if "the collapse of tubes could be expressed by the ordinary laws of the resistance of materials". Unwin then discusses tube collapse on the analogy of this to the failure of long thin columns, and deduces from Euler's formula for columns a similar expression for the collapsing pressures of tubes. After making certain assumptions, he concludes, "The lowest collapsing pressure for long tubes is:

$$P_{\text{min.}} = \frac{8}{3} E \frac{t^3}{d^3}$$

If l is less than 28 t, the collapsing pressure at the limit is:

$$P_{\text{max.}} = \left[\frac{\pi^2 E}{4704} \right] \frac{t}{d}$$

If t is greater than $\frac{1}{36} d$, the formulæ cease to be applicable".[1] The above formulæ are thus proposed only for very thin tubes. Unwin then modified his theory to make it agree with Fairbairn's experiments, and reached as an approximation the formula already quoted on page 5. Like other writers, he did not appreciate the very limited range of Fairbairn's experiments as regards length of tubes. Grashof's attempt to deduce a rational expression for tube collapses was made much earlier, but seems generally to have been overlooked. It is added at the end of his paper on Fairbairn's experiments, in which he gives the empirical formula already noted on page 5. Grashof deduces

$$P = \frac{2k\frac{t}{d}}{1 + \frac{3}{2} a \frac{d}{t}}$$

the formula where P = collapsing pressure: t = thickness of wall; d = diameter of tube; k = yielding strength of the material; and $a = \frac{a - b}{a}$, where a is the maximum diameter, and b the minimum diameter of the distorted tube at the instant of failure.[2]

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[1] Unwin, Institution of Civil Engineers, 1876, Part IV, p. 232.

[2] F. Grashof, Zeitschrift des Vereines deutscher Ingenieure, Vol. III, p. 241.

Curves and Formulæ

An inspection of the data of our experiments shows that the portion of a long tube affected by the collapse from hydraulic pressure is generally not longer than twelve times the diameter, and that for greater lengths the collapsing pressure is independent of the length. The law according to which the collapsing pressure varies inversely as the length, is true only for very short tubes, i. e., tubes shorter than a certain "critical minimum length", which in most cases is from four to six times the diameter. We can thus omit further consideration of all formulæ of the Fairbairn type in which the length appears in the denominator.

All considerations show that the collapsing pressure of a tube is a function of t, the thickness of the tube wall, and also of d, the diameter, varying directly as some function of t, and inversely as some function of d. Further, all the theoretical discussions indicate that this collapsing pressure varies as a function of the ratio $\frac{t}{d}$, i. e., that t and d have the same exponents. The simplest method of showing and studying the relation between p, the collapsing pressure, and the ratio, $\frac{t}{d}$, is the graphic one, constructing curves from the experimental data. In Figs. 11, 12 and 13 such curves are drawn. In all these curves, the ordinates represent the values of P, and the abscissas represent the corresponding values of $\frac{t}{d}$, $\frac{t^2}{d^2}$ and $\frac{t^3}{d^3}$. Fig. 11 is for drawn brass tubes, Fig. 12 for cold drawn seamless steel tubes, and Fig. 13 was made by taking the numerical results from Professor Stewart's paper on lap-welded steel tubes and calculating the ratios. While our tables contain results of a large number of tests of lap-welded tubes, these tubes were all thick and also of about the same thickness, so that they gave but few points of a curve. We relied on the cold drawn steel and the brass tubes for the form of the complete curve, as these tubes were more uniform in thickness, diameter, and probably in material also than the lap-welded tubes. The agreement in the general shape of these curves for tubes of different materials and from independent observations is good evidence of the general reliability of the experimental data. An examination of these curves shows the following:

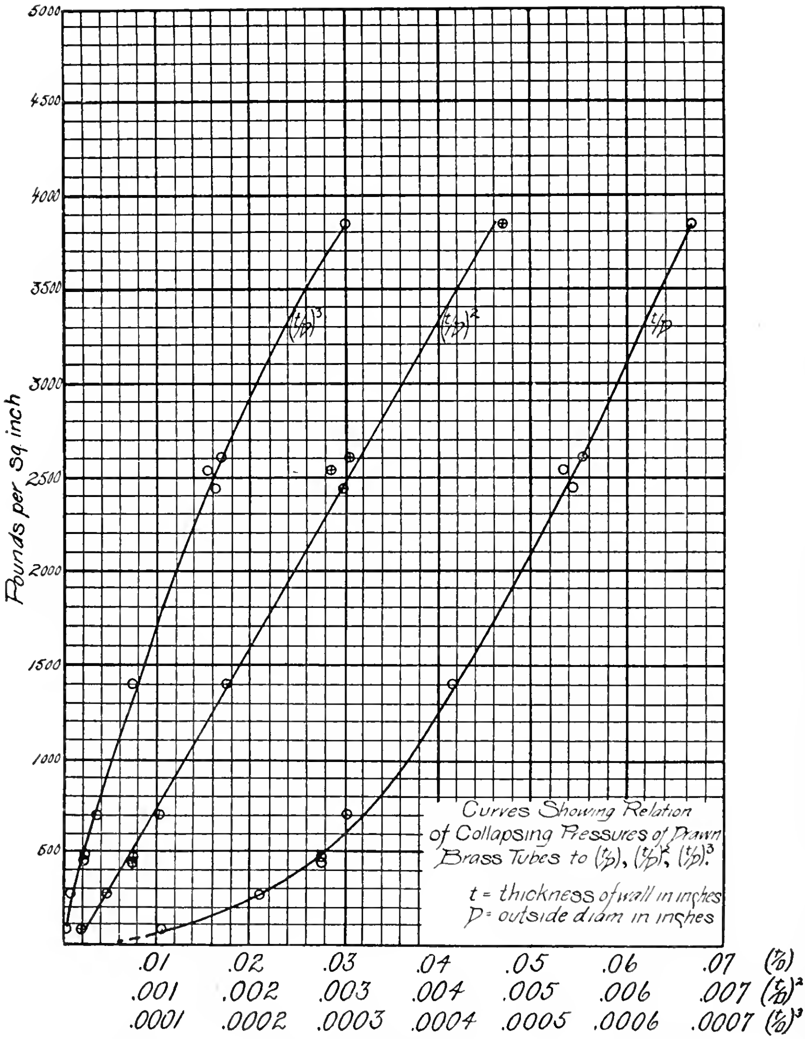

FIG. 11 CURVES SHOWING RELATION OF COLLAPSING PRESSURES OF DRAWN BRASS TUBES TO

$$\left(\frac{t}{d}\right),\quad \left(\frac{t}{d}\right)^2 \text{ and } \left(\frac{t}{d}\right)^3$$

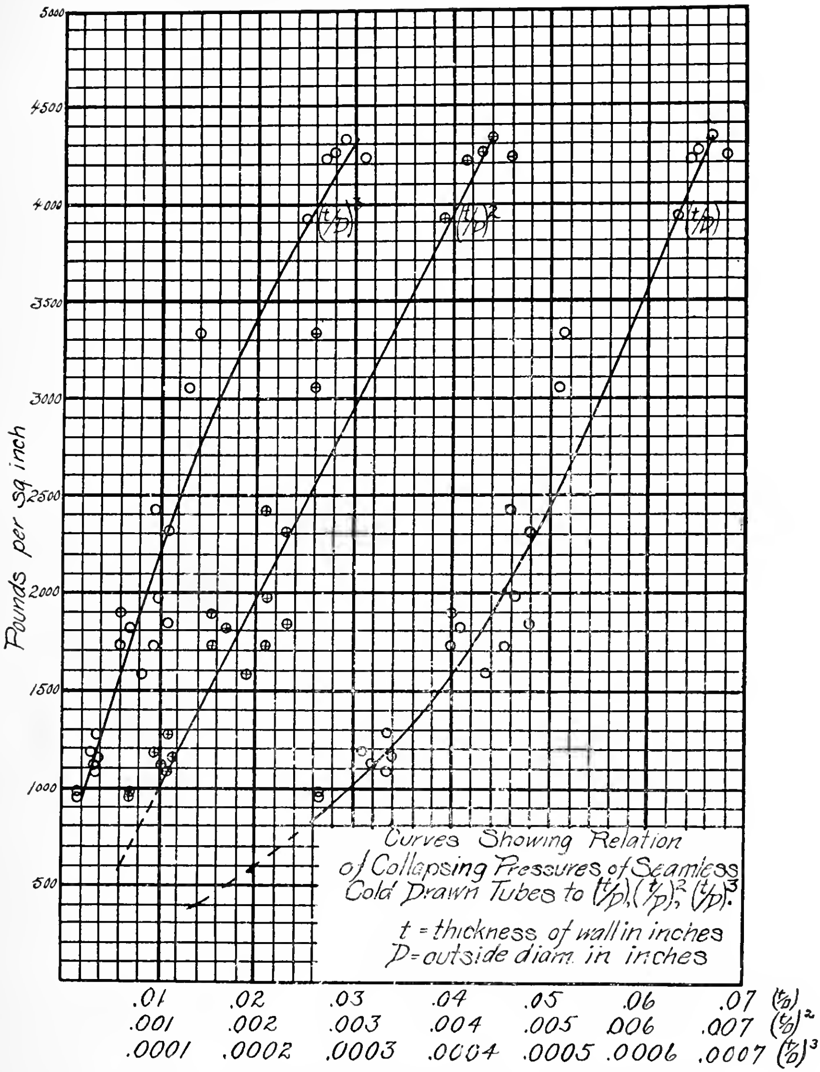

FIG. 12 CURVES SHOWING RELATION OF COLLAPSING PRESSURES OF SEAMLESS COLD DRAWN STEEL TUBES TO

$$\left[\frac{t}{d}\right], \quad \left[\frac{t}{d}\right]^2 \text{ and } \left[\frac{t}{d}\right]^3$$

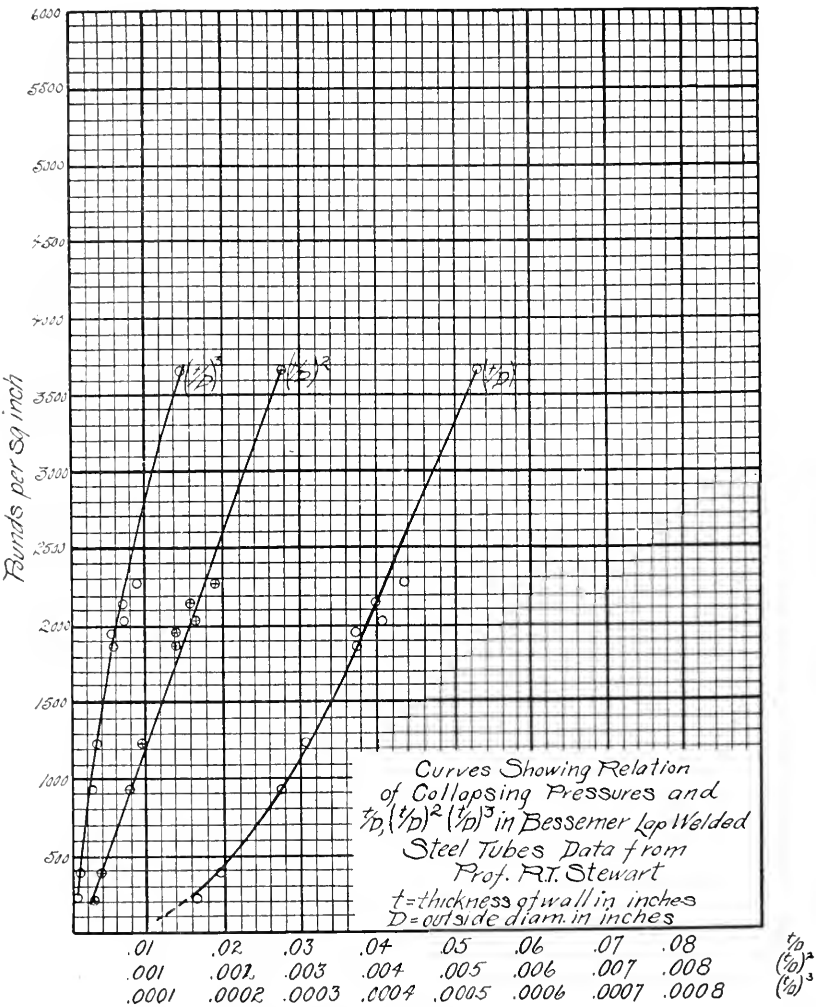

FIG. 13 CURVES SHOWING RELATION OF COLLAPSING PRESSURES AND $\left(\frac{t}{d}\right)$; $\left(\frac{t}{d}\right)^2$ and $\left(\frac{t}{d}\right)^3$ IN BESSEMER STEEL TUBES, DATA FROM PROF. R. T. STEWART

(1) For thin tubes, i. e., for values of $\frac{t}{d}$ below about .025, the formula, $P=k\left[\frac{t}{d}\right]^3$, is very nearly true. This assumes that for this portion of the curve of P and $\left[\frac{t}{d}\right]^3$, the curve is practically a straight line. So far, this is in agreement with the theoretical conclusions of Bryan and Unwin. The limit agrees with the value of $t=\frac{d}{36}$, given by Unwin. The values of k are also of the same order as the coefficient of Bryan's formula, although no very close agreement need be expected, as it is difficult to get extremely accurate readings of the small collapsing pressures. The constants have been calculated and the formulæ are as follows:

(a) For thin brass tubes:

$$P=25,150,000\left[\frac{t}{d}\right]^3$$

(b) For thin cold drawn seamless steel tubes:

$$P=50,200,000\left[\frac{t}{d}\right]^3$$

All of the lap-welded tubes tested by us were thick tubes. This formula with practically the same numerical coefficient applies to the thin tubes given in Stewart's tables of results.

(2) The curve of P and $\frac{t}{d}$ is nearly straight for the thick tubes, i. e., for tubes having a value of $\frac{t}{d}$ greater than about .03. For thinner tubes, the curve bends rapidly toward the axis. The straight part of the curve can evidently be represented by an equation, $P=k\left[\frac{t}{d}\right]-c$, where k and c are constants. We have calculated these constants from our data, and find the following formulæ for tubes having a ratio $\frac{t}{d}$ greater than .03:

(a) For brass:

$$P=93,365\frac{t}{d}-2474;$$

(b) For seamless cold drawn steel:

$$P = 95{,}520 \frac{t}{d} - 2090;$$

(c) For lap-welded steel:

$$P = 83{,}270 \frac{t}{d} - 1025.$$

Professor Stewart found for his lap-welded tubes the formula

$$P = 86{,}670 \frac{t}{d} - 1386.$$

This formula, as thus stated, is purely empirical, and its lower limit is entirely arbitrary. From a suggestion of Professor A. N. Talbot, department of Theoretical and Applied Mechanics, University of Illinois, attention was called to Grashof's rational formula:

$$P = \frac{2k \frac{t}{d}}{1 + \frac{3}{2}\, a \frac{d}{t}}$$

as a possible solution. When plotted for P and $\frac{t}{d}$, assigning constant values to k and a, this gives a curve suggesting the experimental curves but no possible constant values of k and a satisfy the data. It is probable that a is not a constant, being approximately so for thick tubes, but having quite different values for thin tubes. The formula thus becomes too complicated for use. The above formulæ and their limits are suggestive in showing where the stiffness of the material is the important factor, and where the effect of the strength of the material comes in as the controlling factor. Bryan's formula for thin tubes involves the modulus of elasticity, not the strength of the material. If we suppose that such a formula as Grashof's rational form expresses the facts for thick tubes, the yield point of the material is the factor.

(3) An approximate formula of the form $P = k \left(\frac{t}{d}\right)^2$ is suggested by the curves of P and $\left(\frac{t}{d}\right)^2$, particularly for the steel tubes. For cold drawn seamless steel tubes, this approximate formula is

$$P = 1{,}000{,}000 \left(\frac{t}{d}\right)^2.$$

and this can be used for tubes for which $\frac{t}{d}$ is less than .06. For lap-welded steel tubes, the same formula becomes

$$P = 1{,}250{,}000 \left[\frac{t}{d}\right]^2$$

and this can also be used for values of $\frac{t}{d}$ less than .06. This approximate formula has been useful to us in getting probable collapsing pressures, and gives satisfactory rough values for tubes of the most common commercial thickness.

In applying any formula to calculate the collapsing pressure of a particular tube, a considerable factor of safety should be used. The constants in all these formulæ are large, and $\frac{t}{d}$ (or a power of $\frac{t}{d}$) is a comparatively small quantity, so that a small change in the numerical value of $\frac{t}{d}$ greatly affects the result. Lack of uniformity in the material, and slight deformations are also very important factors. It is to the credit of modern manufacturers of tubes that their product is as uniform as these tests show. With the knowledge which this discussion gives of the law of tube collapse, the user of tubes is in a position to calculate with fair approximation the collapsing pressure, particularly if he can get tests made of one or more sample tubes of the material so as to fix the constants.

While the advance in this field of investigation is thus considerable, yet much work remains to be done especially in connecting the subject more closely with the ordinary equations of elasticity.

Bibliography on Collapse of Boiler Tubes

Bach, C.—Berechnung der Wandstarke der Flammroehre: in *Zeitschrift des Vereines deutscher Ingenieure*, October 31, 1891.

Basset, A. B.—On the Difficulties of Constructing a Theory of the Collapse of Boiler Tubes, in *Philosophical Magazine*, September, 1892.

Belpaire, Theodore.—Note sur la résistance des tubes pressées de l'extérieur: in *Annales du Genie civil*, March, 1879. Referred to by C. R. Roelker in *Van Nostrand's Magazine*, Vol. 24, p. 215.

Briggs, Robert.—Editorial comment on article in *Engineering*, Vol. 21, p. 511; also *Journal Franklin Institute*, Vol. LXXII, p. 175.

Brown and Company, John, Sheffield, England.—Report of Test of Four Cambered Furnaces: *Trade Catalog, Marine Specialties*, Fifth Edition, 1902.

Bryan, G. H.—Application of the Energy Test to the Collapse of Long Thin Pipe under External Pressure: in *Proceedings Cambridge Philosophical Society*, Vol. VI, 1888.

Clark, D. K.—Manual of Rules, p. 694, London, 1877.

Strength of Furnace Flues; *London Engineering*, September 21, 1888.

Clark, S. E.—Vol. I, p. 643. Referred to in Kent's Handbook, Fifth Edition, p. 265.

Fairbairn, W.—The Resistance of Tubes to Collapse: in *Philosophical Transactions*, Vol. 148, 1858, pp. 389–413.

Useful Information for Engineers: Vol. II. p. 175, London, 1867.

Report of British Association for Advancement of Science: 1858, p. 174.

On the Collapse of Glass Globes and Cylinders: *B. A. A. S. Report*, 1858, p. 174.

Fletcher, L. E.—Monthly Reports of the Manchester Steam Users Association. Referred to by D. K. Clark in *Engineering*, September 21, 1888.

Grashof, F. W.—Fairbairn's Versuche ueber den Widerstand von Roehren gegen Zusammendrueckung: *Zeitschrift des Vereines deutscher Ingenieure*, Vol. 3, 1859, 234.

Theorie der Elasticitat und Festigkeit, p. 328. Referred to by C. R. Roelker in *Van Nostrand's Magazine*, Vol. 24, p. 212.

Hutton, W. S.—Steam Boiler Construction, p. 179. Fourth Edition, London, 1903.

Julian and Bataille.—Machines à Vapeur p. 240. Reference by C. R. Roelker, p. 211, Vol. 24, *Van Nostrand's Magazine*.

London Engineering.—The Strength of Boiler Flues, Vol. 21, p. 511, June 16, 1876.

Love, A. E. H.—Mathematical Theory of Elasticity, Vol. 2, p. 315, Cambridge, 1903.

Love, G. H.—Sur la résistance des conduits intérieurs à funiél dans les chaudiéres à vapeur: Referred to by Todhunter and Pearson in *History of Theory of Elasticity*, Vol. II, Part I, p. 667, Cambridge, 1893.

Nystrom, J. W.—A New Treatise on Steam Engineering, p. 106. Referred to in Kent, Fifth Edition, p. 265.

Roelker, C. R.—Experimental Investigation of the Resistance of Flues to Collapse, *Van Nostrand's Magazine*, Vol. XXIV, p. 208, March, 1881.

Seaward, John.—Discussion of Formulæ for the Collapse of Boiler Flues: *Journal of Franklin Institute*, Vol. XXVI, p. 349.

Shock, W. H.—Steam Boilers, Their Construction and Management, p. 113, New York, 1880.

Unwin, W. C.—On the Resistance of Flues to Collapse: *Proceedings of the Institute of Civil Engineers*, Vol. XLVI, p. 225. The Strength of Boiler Flues: *London Engineering*, June 9, 1876, Vol. 21, p. 482; also July 7, 1876; also *Journal of Franklin Institute*, Vol. LXXII, p. 171.

Wehage, Zur Berechnung der Flammroehre von Dampfkesseln: *Dingler's Polytechnisches Journal*, pp. 236–243, 1881.

Wilson, Robert.—The Strength of Boiler Flues: *London Engineering*, Vol. 21, June 2, 1876.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

Bulletin No. 1. Tests of Reinforced Concrete Beams, by A. N. Talbot. 1904.

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Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by A. N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by A. P. Carman. 1906.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 6 JUNE 1906

HOLDING POWER OF RAILROAD SPIKES

BY ROY I. WEBBER, C. E., INSTRUCTOR IN CIVIL ENGINEERING

The determination of a proper fastening between the rail and the tie has become a matter of considerable importance. During the period when the supply of suitable hard wood timber was sufficient, the ordinary spike satisfactorily fulfilled the requirements of traffic; but with the increase in the amount of traffic handled, and the heavier weights of cars and locomotives, and also with the use of soft deciduous and coniferous woods for ties, the common spike has proved deficient. Variations in the form of the ordinary spike have been developed, and new forms of spikes have been devised in an attempt to overcome the loss of efficiency attendant upon the use of inferior timbers.

In view of these conditions, and the meager supply of published data on the holding power of spikes in ties, the writer has carried out a series of experiments to determine the resistance to withdrawal offered by the same type of spike in different timbers and by different forms of spikes in the same timber, and also to determine whether or not the preservative has any influence upon this resistance.

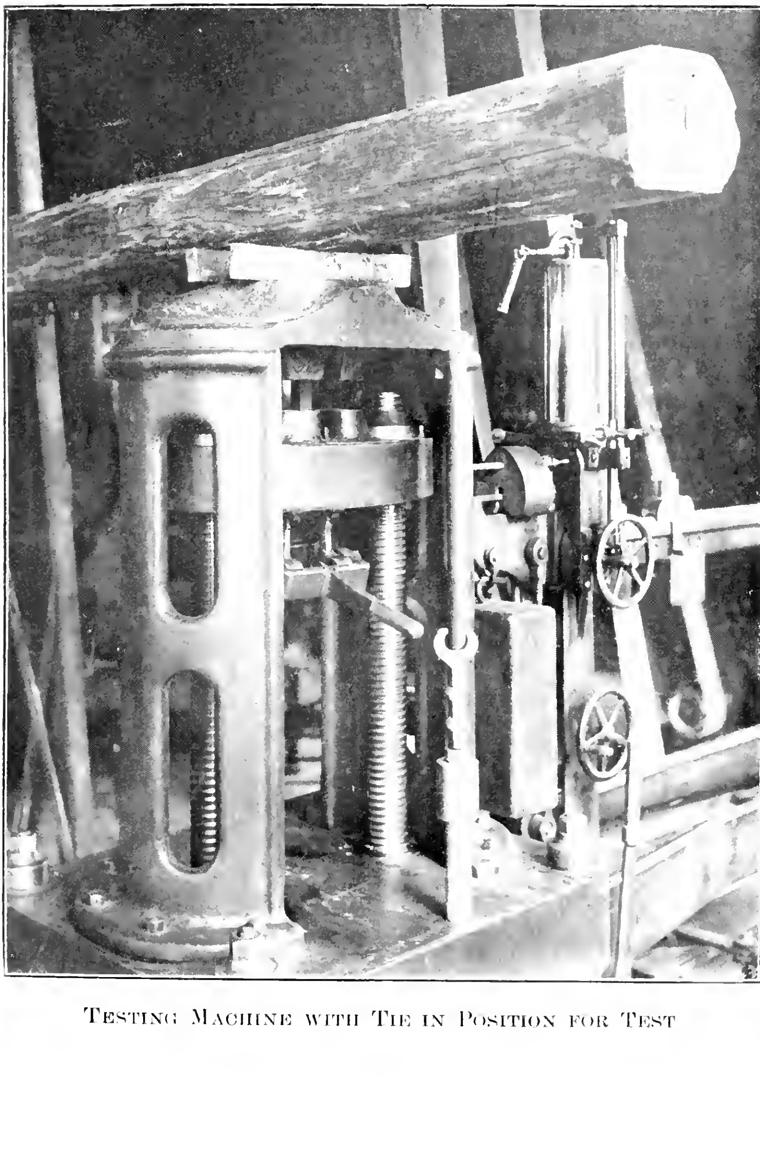
The writer wishes to express his thanks for the hearty cooperation received from the various persons, firms and corporations mentioned in the text. He wishes also to express his indebtedness for personal aid, to Mr. Robert Trimble, Chief Engineer Maintenance of Way, Pennsylvania Lines; Mr. George E.

TABLE I

DESCRIPTION OF THE TIES

No. of Tie	Kind of Timber	Kind of Treatment	Date Treated	Remarks
1	Blue Ash	Zinc-Creosote	1905	Seasoned: sound
2	Blue Ash	Zinc-Creosote	1905	Seasoned; sound
3	Sweet Gum	Zinc-Creosote	1904	Seasoned: sound
4	Water Oak	Zinc-Tannin	1904	Seasoned; sound
5	Water Oak	Zinc-Tannin	1904	Seasoned; sound
6	Red Oak	Zinc-Tannin	1904	Seasoned: sound
7	Red Oak	Zinc-Creosote	1905	Seasoned: sound
8	Red Oak	Zinc-Creosote	1905	Seasoned: sound
9	Red Oak	Zinc-Tannin	1904	Seasoned: sound
10	Rock Elm	Zinc-Creosote	1905	Seasoned: sound
11	Poplar	Zinc-Creosote	1905	Seasoned: sound
12	Elm	....	....	Seasoned; sound
13	Elm	....	....	Seasoned: sound
14	Beech	....	....	Seasoned: sound
15	Elm	....	....	Seasoned: sound
16	Black Oak	Zinc-Creosote	1902	Seasoned
17	Red Oak	Zinc-Creosote	1902	Seasoned
18	Black Oak	Zinc-Creosote	1902	Seasoned
19	Poplar	Zinc-Creosote	1902	Seasoned
20	Loblolly Pine	Zinc-Tannin	1905	Treated December, 1905; sound
21	Lob'y Pine	Zinc-Tannin	1905	Treated Dec: '05; sound
22	Red Oak	Zinc-Tannin	1905	Treated Dec: '05; split
23	Black Oak	Zinc-Tannin	1905	Treated Dec: '05
24	Black Oak	Zinc-Tannin	1905	Treated Dec; '05
25	Water Oak	Zinc-Tannin	1905	Treated Dec; '05
26	Water Oak	Zinc-Tannin	1905	Treated Dec; '05
27	Black Oak	Zinc-Tannin	1905	Treated Dec; '05
28	Red Oak	Zinc-Tannin	1905	Treated Dec; '05
29	Water Oak	Zinc-Tannin	1905	Treated Dec: '05
30	Red Oak	Zinc-Tannin	1905	Treated Dec; '05
31	White Oak	....	....	Seasoned: in track two years Indiana Oak: sap wood showed slight decay
32	White Oak	....	....	
33	White Oak	....	....	Georgia Oak; seasoned; sound
34	Water Oak	Creosote	1904	Sound
35	Burr Oak	Creosote	1904	Sound
36	Beech	Creosote	1904	Sound
37	Elm	Creosote	1904	Sound
38	Beech	....	....	Sound
39	Lob'y Pine	....	....	Seasoned; sound
40	Chestnut	....	....	Seasoned: sound
41	Red Oak	Creosote	1904	Showed tendency to split
42	Beech	....	....	Sound
43	Beech	....	....	Sound
44	Beech	....	....	Sound

PLATE I



Testing Machine with Tie in Position for Test

Boyd, Roadmaster of the Illinois Central Railroad; Mr. A. L. Kuehn, Superintendent of Maintenance of Way, of the Cleveland, Cincinnati, Chicago and St. Louis Railway; Dr. Octave Chanute, President of the Chicago Tie Preserving Company, Chicago, Illinois; and to Professor Ira O. Baker and Professor C. H. Hurd of the University of Illinois.

The Ties

The ties used in these experiments were furnished gratuitously as follows: Nos. 1 to 11, and 16 to 30 by the Chicago Tie Preserving Company, Chicago, Illinois; Nos. 12 to 15 by the Illinois Central Railroad Company; Nos. 31 to 41 by the Cleveland, Cincinnati, Chicago and St. Louis Railroad Company. Table I gives a description of the several ties used. The ties were taken either from the stock pile of the railroad companies or from those of the treating plant. No attempt has been made to trace their history farther back than the place of growth and the date of treatment. Treated ties were used in a majority of the experiments, since in the future, as the inferior grades are pressed into service, the tendency will doubtless be toward the use of preserved timber.

Experiments

Two distinct lines of experiments were undertaken: (1) The determination of the resistance to direct pull of several forms of spikes; and (2) An investigation of the resistance to lateral thrust. Therefore the paper naturally divides itself into two parts: Part I, Resistance to Direct Pull; Part II, Resistance to Lateral Displacement.

All of the experiments were made in the Laboratory of Applied Mechanics, University of Illinois.

PART I RESISTANCE TO DIRECT PULL

The experiments were made with a Riehle 100,000-pound testing machine. Plate I shows the machine with a tie in position for a test. The pulling device for ordinary spikes, also shown in Plate I, was a Verona spike-puller threaded into a piece of steel gripped between the lower jaws of the machine; the pulling device for the screw spikes was of the same general pattern and was designed especially for these tests. A scale graduated to 1-16 of an inch was so set that the distance moved through the lower head of the machine could be measured directly. A load of 500

pounds was applied to insure the tie's having a good bearing before any records were taken. The machine was geared to move at the rate of 5-8 of an inch per minute, which allowed time for carefully balancing the machine and for taking the readings of the scales. Five observations were usually taken; viz., when the lower head of the machine had moved through 1-8, 1-4, 1-2 and 3-4 of an inch, and also at the point at which the maximum fiber resistance was developed. No observations were made after the spike had been pulled 3-4 of an inch, as it would have lost its usefulness long before that point had been reached.

Further consideration of this part of the paper will be continued under the following heads: Art. 1, Holding Power of Ordinary Spikes; Art. 2, Holding Power of Screw Spikes without Linings; and Art. 3, Holding Power of Screw Spikes with Helical Linings.

Art. 1 Holding Power of Ordinary Spikes

The ordinary spikes were received from the following companies, the numbers in this list being the designations in the subsequent tables: Nos. 1 and 2 from the Pennsylvania Railroad Company; Nos. 3 and 4 from the American Iron and Steel Manufacturing Company, Scranton, Pennsylvania; Nos. 5 to 10 from Dillworth, Porter and Company, Pittsburg, Pennsylvania; No. 11 from the W. A. Zelnicker Supply Company, St. Louis, Missouri, and Nos. 12 to 14 from the Illinois Steel Company, Chicago, Illinois.

The nominal dimensions of the four sizes of spikes are shown in Table II. The actual lengths varied considerably from the nominal lengths, usually being less. This was particularly true concerning the 6-inch spike. The actual cross sections were nearly the same as the nominal, the variation in thickness rarely being over 1-64 of an inch. As the range in thickness of the spikes was only 1-16 of an inch, some experiments were made with plain, square and chisel-pointed bars 1-2, 3-4, and 7-8 of an inch thick to determine the relation between the holding power and the cross section. The spikes had differently shaped points, as shown in Table II. Three spikes were used for each experiment, and these three were always of the same size and lot number.

The spikes were driven by Mr. M. Flood, an experienced track foreman detailed for this purpose by the division engineer of the Cleveland, Cincinnati, Chicago and St. Louis Railway.

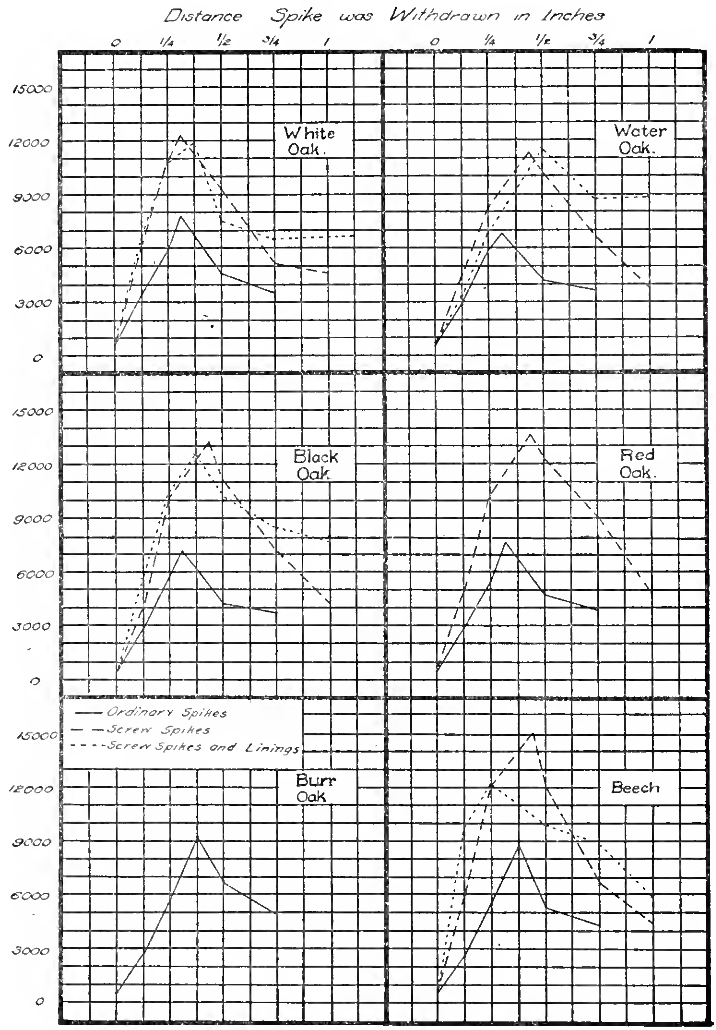
TABLE II

DESCRIPTION OF THE ORDINARY SPIKES

Record Number	Nominal Length, inches	Section, inches square	Area, square inches	Type of Point	Depth Inserted, inches	Condition of Surface of Spike
1	6	5-8	0.372	Chisel	5	Smooth
2	5 1-2	5-8	0.372	Chisel	5	Smooth
3	5 1-2	5-8	0.372	Blunt	5	Smooth
4	5 1-2	5-8	0.372	Blunt	5	Smooth
5	6	5-8	0.372	Sharp	5	Smooth
6	5 1-2	19-32	0.352	Sharp	5	Smooth
7	5 1-2	19-32	0.352	Chisel	5	Smooth
8	6	5-8	0.372	Blunt	5	Smooth
9	5 1-2	9-16	0.316	Blunt	5	Smooth
10	5 1-2	9-16	0.316	Sharp	5	Smooth
11	5 1-2	9-16	0.316	Chisel	5	Smooth
12	5 1-2	9-16	0.316	Sharp	5	Smooth
13	5 1-2	9-16	0.316	Chisel	5	Smooth
14	6	5-8	0.372	Chisel	5	Smooth

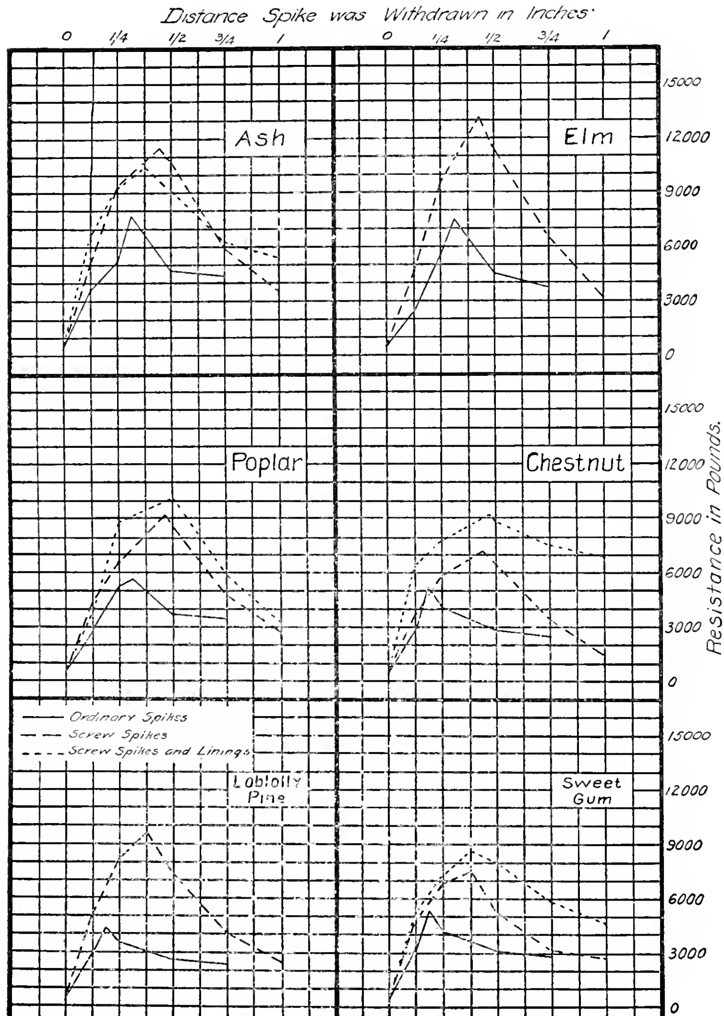
Whole ties were used to insure freedom from splitting in driving the spikes, and care was exercised to avoid driving the spike into knots or cracks. The spikes were driven into the tie to a depth of 5 inches. In some instances, as shown in the record, holes were bored for the ordinary spikes, the hole being 1-16 or 1-8 of an inch less in diameter than the cross sectional dimensions of the spike. The depth of boring was not quite as great as the depth of insertion, so that the pointed end of the spike was forced into the undisturbed wood. Table III gives the detailed numerical results of the tests and Plates II and III show graphically the curves of average resistances of the different ties.

PLATE II



Curves Showing Resistance to Withdrawal of the Spike from the Tie.

PLATE III



Curves Showing Resistance to Withdrawal of the Spike from the Tie.

TABLE III

DETAILED RECORD OF TESTS OF DIRECT PULL OF ORDINARY SPIKES

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of				Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Distance Withdrawn, inches
Blue Ash	1	12	1	1800	4460	5220	4450	6840	3-8
			2	4040	5060	4510	3990	7260	3-16
			3	4270	4340	3860	3370	6330	3-16
			Av.	4150	4630	4530	3970	6810	3-16
	2	6	1	2220	4700	5250	5230	8740	3-8
			2	3390	6940	4710	4710	8020	5-16
			3	2860	5670	4890	4830	8540	3-8
			Av.	3000	5770	4890	4830	8640	3-8
Sweet Gum	3	5	1	2630	1930	2010	2220	4300	3-16
			2	3940	4010	3000	2550	5640	3-16
			3	5180	3920	4620	4560	5180	1-8
			Av.	3920	3960	2690	2470	5040	3-16
	3	14	1	2900	4030	3260	2720	5610	3-16
			2	3470	4100	2750	2780	5370	3-16
			3	3540	3580	3030	2500	4900	3-16
			Av.	3300	3900	3010	2640	5330	3-16
	3	5	1	3030	5100	2930	2930	5100	1-4
			2	2690	5570	4040	3100	5570	1-4
			3	5030	3400	....	....	5700	3-16
			Av.	3580	4370	3440	3420	5440	1-4
	3	11	1	2110	4030	2340	1680	4030	1-4
			2	2780	3190	2320	....	4810	3-16
			3	1680	4100	3730	3340	4980	5-16
			Av.	2190	3770	2790	2510	4610	1-4
	3	3	1	2650	6500	4410	4030	6500	1-4
			2	3890	4100	3590	3340	5460	3-16
			3	2910	6180	4800	4070	6180	1-4
			Av.	3150	5590	4190	3810	6050	1-4

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds For Pull of				Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Distance Withdrawn, inches
Water Oak	4	14	1	2790	6580	4190	3930	7560	5-16
			2	3300	7060	2970	2940	7060	1-4
			3	2220	5330	3920	3200	7740	5-16
			Av.	2770	6320	3660	3360	7450	5-16
	5	14	1	2870	6040	4270	3400	7720	5-16
			2	1610	4460	5060	4240	7780	3-8
			3	....	....	....	....	....	....
			Av.	2240	5250	4660	3820	7750	3-8
	26	14	1	2560	5430	3610	3530	6150	1-4
			2	3440	3340	3050	2590	4960	3-16
			3	3160	....	3200	3210	5810	3-16
			Av.	3050	4380	3290	3110	5640	3-16
	29	14	1	1580	3900	3970	3160	6000	5-16
			2	1470	3550	3450	3090	5110	5-16
			3	2190	4070	2990		4070	1-4
			Av.	1740	3840	3470	3130	5060	5-16
	4	6	1	1960	6030	5420	4530	8690	5-16
			2	2390	5320	....	....	8040	3-8
			3	3200	6380	4380	4100	7320	5-16
			Av.	2520	5920	4900	4320	8020	5-16
	5	6	1	2750	6070	5260	4560	8580	3-8
			2	4330	4890	3430	3040	5270	3-16
			3	1610	4360	3190	3020	4760	1-4
			Av.	2930	5240	3960	3870	6200	1-4
	25	7	1	3370	3860	3380	3180	4910	3-16
			2	1800	5440	3370	3130	5440	1-4
			3	2550	4490	3680	3230	4490	1-4
			Av.	2570	4600	3380	3180	4940	1-4
	26	6	1	3200	5300	4020	3820	5300	1-4
			2	2130	5710	4200	3700	5710	1-4
			3	3500	5820	4620	4340	5820	1-4
			Av.	2940	5610	4280	3950	5610	1-4

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Water Oak	29	6	1	2810	4480	3750	3160	4480	1-4
			2	4620	....	4070	3720	4760	3-16
			3	3720	3450	2910	....	3720	1-8
			Av.	3720	3970	3240	3440	4320	3-16
	4	13	1	2820	5920	4360	4360	9000	3-8
			2	3130	5600	4170	3460	7450	5-16
			3	3430	6330	4440	4060	9000	3-8
			Av.	3160	5980	3320	4260	8380	3-8
	5	11	1	3000	6020	3340	2750	6240	5-16
			2	3200	8010	4720	5300	9180	5-16
			3	3230	5800	3900	3890	6490	5-16
			Av.	3140	6610	3950	3980	7300	5-16
	26	11	1	3080	....	2650	2270	4240	3-16
			2	2270	5090	3360	2940	5090	1-4
			3	1990	5420	3610	3000	5420	1-4
			Av.	2450	5260	5210	2770	4920	1-4
	25	13	1	2440	5100	4230	3640	6450	5-16
			2	3440	6680	4000	3980	6680	1-4
			3	1840	3710	2830	2540	4550	5-16
			Av.	3570	5160	3680	3380	5860	5-16
	34	13	1	2340	5620	5770	5080	9070	3-8
			2	1700	3730	2830	2260	4970	5-16
			3	3360	6560	3600	3010	6560	1-4
			Av.	2470	5300	4070	3950	6870	5-16
	34	14	1	4090	7000	4070	4020	8430	5-16
			2	3090	6780	3550	2900	6780	1-4
			3	3180	7280	4660	2870	8040	5-16
			Av.	3450	7020	4090	3260	7750	5-16
	34	6	1	2370	4720	4940	4730	6400	5-16
			2	3010	6670	5210	4930	7360	5-16
			3	3900	8130	5060	4540	8130	1-4
			Av.	3130	6510	5070	4740	7290	5-16

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Black Oak	16	8	1	3010	6880	5950	4930	9000	3-8
			2	....	7220	....	4380	9100	3-8
			3	3880	8500	4620	3180	8700	5-16
			Av.	3450	7530	5300	4160	8940	3-8
	16	14	1	3230	6110	3270	2890	6110	1-4
			2	....	6280	4120	3760	6540	5-16
			3	2090	4390	3980	3540	7760	3-8
			Av.	2660	5590	3790	3390	6810	5-16
	23	1	1	2980	6740	3460	3290	8210	5-16
			2	3380	7940	4290	3850	7940	1-4
			3	1220	2920	....	4050	9060	1-2
			Av.	2200	5130	3870	3730	8070	3-8
	27	5	1	3430	8070	5300	4740	10000	5-16
			2	....	5910	4500	4170	8970	5-16
			3	2870	7570	4200	3850	7070	1-4
			Av.	3150	7020	4670	4250	8680	5-16
	27	8	1	3510	8470	3370	3370	8470	1-4
			2	2750	7130	2900	2930	8780	5-16
			3	2940	6690	4480	2940	....	1-4
			Av.	3070	7430	4600	3080	8620	1-4
	18	11	1	2650	5240	3340	2670	7130	5-16
			2	....	....	....	....	....	....
			3	2660	6190	5040	4440	8250	9-16
			Av.	2660	5720	4190	3550	7690	5-16
	18	10	1	1700	3410	3330	2570	5860	3-8
			2	2120	3900	3170	2900	5660	3-8
			3	2250	4000	2830	3090	4000	1-4
			Av.	2020	3770	3110	2850	4880	3-8
	16	11	1	3650	5890	4010	3410	5890	1-4
			2	4370	4430	3790	3550	6170	3-16
			3	2400	6230	5320	4380	8620	5-16
			Av.	3470	5520	4370	3780	6890	1-4

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of				Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Distance Withdrawn, inches
Black Oak	27	11	1	4900	7070	3890	3140	7070	1-4
			2	3780	5740	3670	3260	5740	1-4
			3	2730	6550	....	3440	6550	1-4
			Av.	3800	6450	3780	3280	6450	1-4
	24	10	1	3950	6580	4150	3650	6880	1-4
			2	1810	4050	3460	2780	6510	5-16
			3	2960	5390	3600	3410	6500	5-16
			Av.	2910	5340	3740	3280	6530	5-16
	24	4	1	2330	5070	5820	5710	7740	3-8
			2	1880	5570	4320	3740	7010	5-16
			3	3450	6500	4300	3800	7360	5-16
			Av.	2550	5710	4810	4740	7240	5-16
	23	7	1	1820	4690	2800	2880	...	5-16
			2	2250	4110	5520	3880	8790	7-16
			3	2960	7120	4590	3620	7120	1-4
			Av.	2340	5760	3930	3120	7700	3-8
	24	6	1	2520	6110	4040	3490	7070	5-16
			2	1810	5710	4160	3490	7070	5-16
			3	3020	6480	3980	3710	7360	5-16
			Av.	2650	6130	4030	3560	7130	5-16
Red Oak	6	8	1	....	....	....	....	....	....
			2	1870	4750	4410	4190	7190	3-8
			3	2320	6750	4150	3760	8300	5-16
			Av.	2050	5750	4280	3980	7750	3-8
	9	8	1	2210	5460	4310	4100	7300	5-16
			2	2940	6840	3730	3370	7200	5-16
			3	3170	6570	3410	3360	6570	1-4
			Av.	2640	6290	3820	3610	6790	5-16

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of				Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Distance Withdrawn, inches
Red Oak	7	1	1	1450	3300	8700	4920	9210	5-8
			2	2030	4200	7780	4220	8800	7-16
			3	....	....	....	...	....	...
			Av.	1740	3750	8240	4570	9000	1-2
	8	8	1	1570	3100	2910	2600	7330	7-16
			2	1730	3750	3220	2990	7230	7-16
			3	1950	4890	4200	3220	8970	7-16
			Av.	1680	3910	3440	2920	7840	7-16
	22	8	1	2500	3940	2760	2770	5120	3-16
			2	2970	2890	2510	2370	4990	3-16
			3	3490	3490	2460	2370	5270	3-16
			4	2210	4670	2570	2550	4670	1-4
			5	3770	3250	2620	2440	5150	3-16
			6	2620	5490	3780	3400	5490	1-4
			Av.	2930	3950	2800	2650	5120	3-16
	41	1	1	2170	4400	4540	3630	7040	5-16
			2	3900	3650	2230	2420	6040	3-16
			3	1930	4300	2690	2530	5650	5-16
			Av.	2660	4110	3150	2860	6240	1-4
	17	1	1	1710	5030	5420	6260	9720	3-8
			2	2240	5240	9900	6710	11900	1-2
			3	3280	6400	7550	7020	10940	7-16
			Av.	2410	5560	7620	6660	10850	3-8
	6	12	1	3520	4480	3300	2910	5950	3-16
			2	3700	....	3500	3640	6930	1-4
			3	3690	....	3710	3080	4460	3-16
			4	3320	4350	3550	2990	6240	3-16
			Av.	3550	4410	3520	3150	5900	3-16
	6	11	1	2150	5330	4640	3420	7580	5-16
			2	2990	7830	4570	3200	7830	1-4
			3	3240	7000	4710	3670	8280	5-16
			Av.	2760	6740	4640	3430	7890	5-16

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Red Oak	7	12	1	2430	5010	7120	5630	9080	3-8
			2	3430	6110	4930	4300	7020	5-16
			3	....	....	....	....	....	....
			Av.	2930	5560	6030	4960	8030	3-8
	9	12	1	3530	5410	3790	3680	5410	1-4
			2	3000	6280	3950	3510	6280	1-4
			3	3720	7140	4350	4300	7140	1-4
			Av.	3420	6280	4030	3830	6280	1-4
	9	13	1	3270	....	3790	3630	7030	1-4
			2	3740	4600	3730	3110	6660	3-16
			3	3690	4610	3540	3180	6130	3-16
			Av.	3560	4600	3680	3320	6610	3-16
	17	12	1	....	....	11620*	....	....	....
			2	....	....	11230	...	....	....
			3	....	....	10630	....	....	...
			Av.	....	....	11490	....	....	....
	28	12	1	....	....	3430	3130	6390	1-4
			2	3910	7150	4410	3480	7150	1-4
			3	3810	5000	4270	3670	6760	3-16
			Av.	3860	6080	4040	3530	6770	1-4
	28	11	1	....	....	5200	3710	8200	5-16
			2	6250	4000	3280	2600	6250	1-8
			3	2880	6870	3740	3280	6870	1-4
			Av.	4570	5440	4070	3200	7100	1-4
	8	12	1	3030	6800	6080	4950	9420	5-16
			2	2680	....	....	....	...	....
			3	3580	6250	6680	4640	9240	3-8
			Av.	3060	6530	6380	4790	9330	5-16

*This was the first tie tested, and gave unusually high results.

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of				Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Distance Withdrawn, inches
Red Oak	22	13	1	2440	5810	3270	3340	5810	1-4
			2	2850	5040	2770	2170	5040	1-4
			3	1880	4530	3700	3450	6280	3-8
			Av.	2390	5130	3250	2990	5710	1-4
	30	12	1	3700	3960	2950	2460	5500	3-16
			2	1700	3560	2920	3150	4720	3-8
			Av.	2700	3760	2940	3010	5110	1-4
	30	10	1	1680	3580	3070	3030	5570	3-8
			2	2020	4070	2490	2480	5220	5-16
			3	2540	4590	3070	2890	6080	3-8
			Av.	2040	4070	2870	2760	5620	3-8
	41	12	1	4500	7690	3530	3340	7690	1-4
			2	4750	....	3200	3300	7210	3-16
			3	1930	5840	3370	3750	7430	5-16
			Av.	3730	6760	3360	3460	7440	1-4
	41	9	1	3670	7950	3100	2420	7950	1-4
			2	3760	7110	3450	3300	7110	1-4
			3	4620	4500	4450	3960	6230	3-16
			Av.	4010	6520	3660	3220	7090	1-4
	28	3	1	....	....	5290	4000	8290	5-16
			2	....	....	4940	4420	7840	5-16
			3	....	....	4190	3510	4940	1-8
			Av.	....	....	4810	3970	7020	5-16
Burr Oak	35	1	1	2960	4960	8240	5560	8240	1-2
			2	1410	3570	9450	6220	9450	1-2
			3	3090	6850	5930	5600	9440	3-8
			Av.	2490	5130	7540	5780	9040	1-2
	35	11	1	4020	8640	6210	5770	10560	3-16
			2	2200	3390	9240	4500	9240	1-2
			3	2230	5020	6290	5250	9000	3-8
			Av.	2820	5680	7250	5170	9600	3-8

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Burr Oak	35	8	1	2690	7040	4820	4110	10090	3-8
			2	2740	5840	4060	3700	7920	3-16
			Av.	2710	6440	4440	3950	9000	1-4
White Oak	31	1	1	3240	7030	3400	3140	7030	1-4
			2	2430	5870	4390	3850	7580	3-8
			3	3700	7500	4180	3330	7500	1-4
			Av.	3150	6800	3990	3440	7370	3-16
	31	14	1	....	4020	3600	3280	7830	3-16
			2	3960	7100	4000	3750	7100	1-4
			3	2250	5580	3650	3200	8980	3-8
			Av.	3110	5560	3750	3410	7940	3-16
	33	1	1	4220	3570	3810	3040	7520	3-16
			2	1950	3670	4640	3340	6940	3-8
			3	3190	5260	3810	3500	6410	5-16
			Av.	3120	4160	4090	3290	6990	5-16
	32	7	1	3860	9440	5930	4650	9440	1-4
			2	3460	6400	3710	3680	8650	5-16
			3	1610	3740	4670	5570	9360	1-2
			Av.	2980	6530	4770	4300	9150	3-8
	33	7	1	4790	3910	2860	2530	5750	3-16
			2	4150	4930	3510	3270	6500	3-16
			3	4630	3840	3070	2450	6030	3-16
			Av.	4520	4230	3150	2750	6090	3-16
	32	10	1	2400	3490	8280	3820	8280	1-2
			2	3100	4840	5410	3880	10190	3-8
			3	2570	6410	10670	4400	10670	1-2
			Av.	2690	4910	8120	4030	9710	1-2
	33	10	1	2930	5490	2390	2330	5490	1-4
			2	3080	6360	2860	2460	6360	1-4
			3	3890	6810	3540	3360	6810	1-4
			Av.	3300	6220	2930	2720	6220	1-4

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
White Oak	32	9	1	3630	7500	5340	4650	9640	3-8
			2	2960	6760	4250	4500	10650	3-8
			3	3490	8270	4810	4590	10750	5-16
			Av.	3360	7510	4800	4430	10350	3-8
	31	3	1	....	....	5200	4330	8380	3-8
			2	4000	7490	3980	3770	7490	1-4
			3	4100	8450	5010	4240	8450	1-4
			Av.	4050	7920	4730	4080	8770	3-16
	33	4	1	4200	....	4330	3790	7330	3-16
			2	4200	7530	4390	3630	7530	1-4
			3	5900	3850	3100	2790	6590	3-16
			Av.	4830	5690	3940	3410	7150	3-16
Rock Elm	10	5	1	2250	6530	4460	4420	8280	5-16
			2	3260	7160	4620	3850	7160	1-4
			3	2910	5880	4650	4340	7300	3-8
			Av.	2810	6520	4580	3210	7910	5-16
	10	2	1	1920	3770	6060	5310	7410	7-16
			2	....	....	....	....	....	....
			3	1960	4510	4420	4160	7730	3-8
			Av.	1940	4140	5240	4730	7570	3-8
	10	11	1	3730	7760	4310	3930	7760	1-4
			2	2800	5820	4460	3580	6800	5-16
			3	3300	6270	4120	3550	7840	5-16
			4	1600	6070	5030	4140	7700	5-16
			5	....	7810	5210	4490	7810	1-4
			Av.	2800	6950	4620	3340	7600	5-16
Red Elm	13	14	1	1240	....	6430	4380	9230	7-16
			2	3000	6500	5080	4960	10040	7-16
			3	1760	5970	....	4040	8810	3-8
			Av.	2000	6235	5750	4460	9350	5-16

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Red Elm	13	2	1	1930	3990	4540	3760	7730	5-16
			2	2240	3860	5250	3970	8100	7-16
			3	1960	4200	4540	3850	7120	3-8
			Av.	2040	4020	4770	3890	7650	7-16
	13	10	1	2810	4930	4850	3510	7550	3-8
			2	2450	4800	4930	3740	7430	3-8
			3	2140	5030	3790	3210	8690	7-16
			Av.	2460	4920	4520	3490	7890	3-8
White Elm	12	14	1	1750	4500	3270	2720	5330	3-8
			2	2810	5500	3530	3010	5590	5-16
			3	1890	5610	3620	2770	5610	1-4
			Av.	2150	5200	3470	2830	5510	5-16
	12	5	1	2460	5790	3590	2980	6280	5-16
			2	2140	5410	2830	2770	5410	1-4
			3	1770	5270	2520	2430	5270	1-4
			Av.	2120	5490	2980	2720	5650	1-4
	15	5	1	2630	6330	5580	....	9500	3-8
			2	3810	7260	4680	4310	9560	3-8
			3	2810	6100	4160	3620	8050	5-16
			Av.	3080	6560	4770	4000	9030	3-8
	37	5	1	2490	8130	3900	3660	8130	1-4
			2	....	5760	4040	3330	6650	5-16
			3	2790	6540	3770	3420	7460	5-16
			Av.	2640	6810	3910	3470	7410	5-16
	15	13	1	1600	4600	...	5900	9670	7-16
			2	2230	5770	5530	4820	8760	3-8
			3	1450	4200	9310	6190	9310	1-2
			Av.	1760	4860	7420	5630	9250	7-16
	12	10	1	1990	3560	3350	2700	5370	3-8
			2	1920	4320	3540	2690	5450	3 8
			3	1830	3930	2360	1650	4100	1-4
			Av.	1910	3970	3080	2010	4970	3-8

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of				Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Distance Withdrawn, inches
White Elm	15	12	1	....	5590	4670	3810	7860	3-8
			2	2430	5630	3870	3350	6140	5-16
			3	2600	5550	3140	....	5550	1-4
			Av.	2510	5920	3890	3580	6520	5-16
	37	2	1	2100	4710	3390	3330	7170	3-8
			2	2920	5160	4070	3840	6310	5-16
			3	3150	5900	4300	3860	7570	3-8
			Av.	2390	5290	3920	3680	7020	3-8
Beech	14	6	1	....	....	5390	4670	7680	1-4
			2	2870	5150	4870	4320	7190	3-8
			3	2230	5660	5310	4940	7820	5-16
			Av.	2550	5400	5190	4470	7560	5-16
	36	6	1	4330	4740	4400	4510	7120	3-8
			2	3610	8100	6230	5320	8560	1-4
			3	2640	8120	5470	4640	9080	5-16
			Av.	3530	6990	5030	4820	8250	5-16
	14	2	1	2550	4740	4570	4100	7670	5-16
			2	2200	5570	5690	4190	8170	3-8
			3	2120	4910	4800	3970	7860	3-8
			Av.	2290	5070	4700	4090	7900	3-8
	36	2	1	3210	5940	4010	3840	8460	3-8
			2	3110	6900	4170	3900	10400	3-8
			3	2120	5440	5240	4130	8270	5-16
			Av.	2850	6090	4470	3960	9040	3-8
	14	9	1	2660	5070	....	3560	8130	3-8
			2	1500	2820	9910	5060	9910	1-2
			3	1490	3810	8900	5280	9220	7-16
			Av.	1880	3900	8960	4630	9090	7-16
	36	9	1	2130	4900	4240	4210	9890	3-8
			2	2940	6640	3860	3650	9430	5-16
			3	2370	4920	3830	3600	8900	3-8
			Av.	2480	5490	3980	3820	9410	3-8

TABLE III—*Continued*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Poplar	11	2	1	2700	4690	3980	3520	4690	1-4
			2	4690	....	3240	2890	4980	3-16
			3	3000	5100	3240	2900	5100	1-4
			Av.	3460	4890	3490	3100	4920	1-4
	19	2	1	2750	4510	4400	3980	6990	3-8
			2	2710	5270	2840	2610	5270	1-4
			3	3100	6050	4080	3650	6050	1-4
			Av.	2850	5240	3760	3410	5900	1-4
	11	12	1	2220	5130	2960	2750	5350	5-16
			2	2750	4940	3800	3590	5070	5-16
			Av.	2480	5040	3280	3170	5210	5-16
	19	12	1	2610	5670	....	....	6250	5-16
			2	2460	6220	4400	4170	7040	5-16
			Av.	2530	5990	4400	4170	6650	5-16
Chestnut	40	14	1	2300	3100	2410	2260	4300	3-16
			2	2330	2600	2860	2460	4060	3-16
			3	3730	3370	2370	2100	5050	3-16
			Av.	2490	3060	2540	2270	4470	3-16
	40	5	1	....	....	....	....	5830	3-16
			2	3010	2720	2650	2650	5180	3-16
			3	3300	3570	2950	2400	5500	3-16
			Av.	3150	3150	2800	2520	5510	3-16
	40	12	1	3320	6230	3050	2270	6230	1-4
			2	5110	....	....	....	5110	1-8
			3	2000	4000	2490	2430	4000	1-4
			Av.	3480	5110	2770	2350	5110	1-4
	40	4	1	1300	3780	3170	2940	5420	3-16
			2	2300	5420	3360	2780	5420	1-4
			3	2440	5640	3190	2590	6220	5-16
			Av.	2850	4950	3240	2770	5690	1-4

TABLE III—*Concluded*

Kind of Tie	Tie No.	Spike No.	Test No.	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Distance Withdrawn, inches
Loblolly Pine	39	14	1	3390	2970	2620	2590	3390	1-8
			2	3760	3980	2790	2420	3980	1-4
			3	4050	2860	2020	1850	4050	1-8
			Av.	3730	3270	2480	2290	3810	1-8
	21	14	1	2880	4550	2370	1870	4550	1-4
			2	1980	2110	1890	1570	3520	3-16
			3	4510	3910	3340	2880	5200	3-16
			Av.	3120	3520	2560	2110	4420	3-16
	20	5	1	2250	4550	2930	2540	4550	1-4
			2	2810	2670	2720	2640	4570	3-16
			3	3610	....	....	...	3610	1-8
			4	1890	2690	2290	2030	3710	3-16
			Av.	2640	3270	2650	2410	4110	3-16
	21	10	1	3570	4450	2500	2230	4450	1-4
			2	2550	4890	3400	3020	4890	1-4
			Av.	3060	4670	2950	2630	4670	1-4
	20	3	1	3090	4800	2730	2320	4800	1-4
			2	2610	2330	2300	2030	3440	3-16
			3	1870	3810	2510	2280	3810	1-4
			Av.	2860	3650	2510	2210	4020	1-4
	39	6	1	3110	2120	2170	1710	3110	1-8
			2	1560	3880	3060	2380	3880	1-4
			3	1630	3330	2640	2650	3330	1-4
			Av.	2100	3110	2960	2250	3440	1-4

A study of the results of Table III has been made to determine: (A) Comparative holding power in untreated ties; (B) Comparative holding power in treated ties; (C) Comparative holding power of the same timber, treated and untreated; (D) Effect of preservative on the holding power; (E) Relation between the cross section of the spike and holding power; (F) Relation between the depth of pene-

tration and the holding power; (G) Effect of the point of the spike on the holding power; (H) Effect of bored holes on the holding power; (I) Effect upon the holding power of re-driving the spike.

A Comparative Holding Power in Untreated Ties

Table IV is compiled from Table III to show the average holding power for different untreated ties. Each result in Table IV is the average of the corresponding results in Table III.

TABLE IV

AVERAGE HOLDING POWER IN UNTREATED TIES

Kind of Tie	No. of Tests	No. of Spikes	Resistance in Pounds for a Pull of		Maximum Resistance		Resistance in per cent of that in White Oak		
			1-8 inch	1-4 inch	Pounds	Distance Pulled, inches	1-8 inch	1-4 inch	Maximum
White Oak	10	30	3510	3950	7870	5-16	100	100	100
Elm	11	33	2310	5390	7290	3-8	66	136	93
Beech	3	9	2240	3790	8180	3-8	64	96	104
Chestnut	4	12	2990	4070	5190	3-16	86	103	66
Loblolly Pine	2	6	2920	3190	3630	3-16	85	81	46

Table IV shows the comparative holding power of five kinds of timber. The last three columns show the holding power in terms of that of white oak. It is thought that a pull of 1-4 of an inch gives results which are of more value in comparing the holding power of the different kinds of ties than the results for either greater or less distances, since the results for the 1-4-inch pull represent the resistances of the various timbers to the withdrawal of the spike for a distance which should not be exceeded in practice, and since the maximum resistance and the results for a pull of 1-8 of an inch represent the resistances for distances which are therefore not of so much consequence as the 1-4-inch pull. Notice that with chestnut and loblolly pine the maximum resistance occurs at 3-16 of an inch, which is a reason for comparing their maximum resistance with that of white oak at 1-4 of an inch instead of with its maximum resistance, as in Table IV. If this is done, the efficiencies of chestnut and loblolly pine for a 1-4-inch pull or less are 131 and 85 per cent respectively.

The fact that the maximum resistance did not occur until the spike had been pulled from 3-16 to 3-8 of an inch is interesting. While the spike is being driven the fibers of the wood are bent downward and are pressed outward, and as the spike is withdrawn the friction between the spike and the wood tends to draw the fibers into their original position, which causes them to crowd laterally against the spike and also toward the surface of the tie, until finally the external pull exceeds the internal resistance and the spike slips. When the fiber structure is open, there is considerable cellular space for the displaced fibers to occupy, and therefore the maximum resistance is low, and is quickly attained; but when the fiber structure is compact, the reverse is true.

As the loblolly pine ties should always be preserved, the results in Table IV for this timber are of doubtful value. For the best results elm ties also should be treated; but as some species of elm do not absolutely require treatment, elm is properly included in Table IV. Arranging these timbers in the descending order of their resistances for a 1-4-inch pull, we have elm, chestnut, white oak, beech and loblolly pine.

The maximum holding power for the first three timbers in Table IV is satisfactory, but that for the last two is quite low. The last fact indicates that when timber of the softer varieties or timber having loose fiber structure is used for ties, some more efficient form of fastening should be devised.

B Comparative Holding Power in Treated Ties

Table V is compiled from Table III to show the average holding power obtained with various treated ties, each result in this table being the mean of the corresponding values in Table III. The average results obtained with untreated white oak are also included so that comparisons can be made.

The average for the resistances for all of the treated timbers is shown at the foot of the table. Excluding the last two timbers, the average resistance for the 1-4-inch pull is 5690 pounds. The maximum resistance of the last two timbers should be averaged with the resistances of the others for the 1-4-inch pull, in which case the average resistance for all of the timbers for a 1-4-inch pull or less is 5400 pounds.

Table V shows that the resistances of the several timbers do not differ widely, and that the soft timbers give results which

TABLE V

AVERAGE HOLDING POWER IN TREATED TIES

Kind of Tie	No. of Tests	No. of Spikes	Resistance in Pounds for a Pull of		Maximum Resistance		Resistance in per cent of that of White Oak		
			1-8 inch	1-4 inch	Pounds	Distance Pulled, inches	1-8 inch	1-4 inch	Maximum
White Oak (Untreated)	10	30	3510	3950	7870	5-16	100	100	100
Water Oak	16	48	2870	5730	6780	5-16	82	145	86
Black Oak	13	39	2910	5890	7230	5-16	83	149	92
Red Oak	20	60	2950	5350	7730	5-16	84	135	98
Burr Oak	3	9	2670	5750	9210	3-8	76	145	117
Ash	2	6	3570	5200	7730	5-16	101	131	98
Elm	5	15	2590	5940	7500	5-16	74	150	96
Beech	3	9	2950	6190	8900	3-8	84	157	113
Poplar	4	12	2830	5290	5670	5-16	81	134	72
Loblolly Pine	4	12	2920	3780	4310	1-4	83	109	55
Sweet Gum	5	15	3230	5320	5300	3-16	92	96	67
Av.	....	....	2950	5320	7040	....	84	135	89

compare favorably with those obtained for the hard woods. This table also shows that the range for the maximum resistances is much greater than that for either the 1-8-or the 1-4-inch pull. The resistances for the different species of oak are very nearly the same, the mean for a 1-8 inch pull being 2850 pounds, for a 1-4-inch pull 5680 pounds and for the maximum 7740 pounds. Notice that with nearly all of the timbers the maximum resistance was obtained after the spike was pulled more than 1-4 of an inch, but there is no apparent relation between the amount of the holding power and the distance through which the spike has been pulled.

Comparing the resistances of treated timbers with that of untreated white oak, we see that the initial resistance of the white oak is higher than any of the other woods except one; while on the other hand, the resistance at 1-4 of an inch in white oak is less than in any of the other woods save one. The maximum resistances of all but the last three timbers are practically the same.

Considering the uniformity of the results obtained with a pull of 1-4 of an inch in the few timbers which were available, there appears to be no strong reason for much discrimination between the different treated timbers.

C *Comparative Holding Power of the Same Timber, Treated and Untreated*

Table VI has been compiled from Table III for the purpose of studying the effect of the treatment upon the holding power of a timber.

TABLE VI

RELATIVE HOLDING POWER IN TREATED AND UNTREATED TIES

Kind of Tie	No. of Ties	No. of Spikes	Condition of Tie	Resistance and Gain in Pounds Due to Treatment					
				1-8 in. Pull	Gain	1-4 in. Pull	Gain	Maximum Resistance	Gain
Elm	3	27	Untreated	2310		5390		7290	
	2	15	Treated	2590	280	5940	550	7500	210
Beech	1	9	Untreated	2240		3790		8180	
	1	9	Treated	2950	710	6190	2400	8900	820
Loblolly Pine	1	6	Untreated	2920		3190		3630	
	2	12	Treated	2920	000	3730	640	4310	680
Red Oak	3	15	Untreated	......		......		6460	
	4	21	Treated	......		.....		7730	1270

Table VI shows that higher resistances are developed in treated than in untreated ties. The average increase due to treatment for a 1-8 inch pull was 330 pounds; for a 1-4 inch pull, excluding the seemingly unreasonable increase in beech, 685 pounds; and for the maximum resistance 747 pounds.

Considerable reliance is placed upon the conclusions drawn from Table VI, inasmuch as the methods of making the tests were exactly the same for the treated and untreated ties, and since the same number of spikes, fifty-seven, was used in both cases, and also since the preserved ties were treated by different processes and at different plants.

The increased resistance due to treatment has two causes: (1) The presence of the preservative in the cells, thus reducing the space into which the fibers can crowd as the spike is withdrawn; and (2) The hardening of the fibers by the steaming, preparatory to treatment, which renders them less pliable.

The movement which took place among the fibers near the surface of the tie is interesting. In the untreated ties there was a crumpling of the fibers close to the spike, while the fibers in the treated ties were torn out in deep slivers extending from the spike to the blocks which supported the tie.

D Effect of the Preservatives on the Holding Power

Three distinct kinds of preserving solutions were used in the ties tested,—creosote, zinc-creosote and zinc-tannin.

Table VII has been compiled from Table III to study the effect produced by the treating solution upon the holding power of the tie.

Table VII does not show any marked difference between the resistances in ties treated with the different preservative solutions. For example, the maximum resistance of the red oak is lower when treated with zinc-tannin than when treated with zinc-creosote, but the reverse is true of the initial resistance of the red oak and also of the maximum resistance of black oak. With elm the initial resistance is higher in creosoted ties than in those treated with zinc-creosote, but the maximum resistance is lower. If any rating were made in order of efficiency, it would appear about as follows: (1) creosote, (2) zinc-creosote, and (3) zinc-tannin. However, there are too many uncertain quantities involved to make such a rating reliable: and morever, the effect of the treating solution upon the holding power is only one of the many elements which must be considered when choosing between the different treating solutions.

E Relation between the Cross Section of the Spike and the Holding Power

The question to be answered here is, which size of spike will develop the highest holding power. To answer this question, Table VIII showing the relation between the cross section and the holding power has been compiled from Table III.

From a study of the results of Table VIII it will be noticed that no general rating can be made for the various sized spikes in order of the resistances developed, since the spike which develops the lowest holding power for the 1-8-inch or the 1-4-inch pull seldom develops the highest maximum resistance. For example, in white oak, the 19-32-inch spike developed the highest resistance for the

TABLE VII

EFFECT OF DIFFERENT PRESERVATIVES ON THE HOLDING POWER

Kind of Tie	Tie No.	Preservative	Resistance in Pounds for a Pull of 1-8 inch	Resistance in Pounds for a Pull of 1-4 inch	Maximum Resistance, Pounds
	Comparison of Zinc-Tannin and Creosote				
Water Oak	4, 5, 25, 26, 29	Zinc-Tannin	2380	5010	6260
	34	Creosote	3020	6270	7310
Red Oak	6, 9, 22, 28, 30	Zinc-Tannin	3170	5470	6580
	41	Creosote	3120	5800	6920
	Comparison of Zinc-Creosote and Creosote				
Red Oak	7, 8	Zinc-Creosote	2350	4940	8500
	41	Creosote	3120	5800	6920
Elm	10	Zinc-Creosote	2520	5870	7690
	37	Creosote	2600	6350	7210
	Comparison of Zinc-Tannin and Zinc-Creosote				
Red Oak	6, 7, 8, 9, 22	Zinc-Creosote	2350	4940	8500
	28, 30	Zinc-Tannin	3170	5470	6580
Black Oak	16, 18	Zinc-Creosote	2850	5620	7040
	23, 24, 27	Zinc-Tannin	2830	5620	7550

1-8-inch pull, but the 9-16-inch spike developed the highest resistance for the 1-4-inch pull, and also the highest maximum resistance. In black oak the highest resistance for the 1-8-inch pull was developed by the 9-16 spike, but that for the 1-4-inch pull was developed by the 19-32-inch size and the maximum resistance by the 5-8-inch spike. Averaging all of the resistances for the 1-8-inch pull, the 1-4-inch pull and the maximum resistance collectively, we see that the average holding power of the 9-16-inch spike is 4990 pounds, for the 19-32-inch spike 5420 pounds and for the 5-8-inch spike 5290 pounds. Because of the large number of spikes tested, seventy-two 9-16-inch, thirty-six 19-32-inch, and one hundred and two 5-8-inch, and the irregularity of the results, it was decided that no conclusions could be drawn from Table VIII as to the relative holding power of the different sizes of spikes. However, the thick-

TABLE VIII

RELATION BETWEEN THE CROSS SECTION OF THE SPIKE AND ITS HOLDING POWER

Kind of Tie	No. of Ties	No. of Spikes	Condition of Tie	Size of Spike, inches	Resistance to Withdrawal, Pounds: 1-8 in. Pull	Resistance to Withdrawal, Pounds: 1-4 in. Pull	Resistance to Withdrawal, Pounds: Maximum Resistance
White Oak	2	9	Seasoned	9-16	3110	6280	8760
	2	6		19-32	3750	5380	7620
	3	15		5-8	3650	6030	7620
Black Oak	4	15	Treated	9-16	2910	5340	6530
	2	6		19-32	2650	6130	7130
	4	18		5-8	2550	5710	7240
Water Oak	5	15	Treated	9-16	2960	5560	6670
	6	18		19-32	2970	5310	6010
	5	15		5-8	2650	5360	6730
Red Oak	7	21	Treated	9-16	2300	4760	7650
	9	36		5 8	3260	5990	6780
Beech	1	3	Seasoned	9-16	1880	3900	9410
	1	3		19-32	2550	5400	7660
	1	3		5-8	2290	5070	7900
	1	3	Treated	9-16	2480	5490	9410
	1	3		19-32	3530	6990	8250
	1	3		5-8	2850	6090	9040
Sweet Gum	1	6	Treated	9-16	2190	3770	4610
	1	12		5-8	3490	4450	5460

ness of the spikes varied by only 1-16 of an inch or about 10 per cent, and their areas by only 0.075 of a square inch or about 20 per cent.

To test still further the relationship between the size of the spike and the holding power, a series of experiments was made with plain square rods with the results shown in Table IX. Each result is the mean of fifteen tests in a single kind of timber.

TABLE IX

EXPERIMENTS WITH PLAIN SQUARE RODS IN BEECH TIMBER

Size of Rod	Area, sq. in.	Average Maximum Results, pounds	Increase for each Increment			
			Area		Resistance	
			square inches	per cent	pounds	per cent
Successive increments in the size of the rod = 1-8 inch						
1-2 inch square	0.250	6280	.....	..	....	..
5-8 inch square	0.391	6970	0.141	53	690	11
3-4 inch square	0.562	9070	0.171	44	2600	37
7-8 inch square	0.765	9380	0.203	35	310	3
Successive increments in the size of the rod = 1-16 inch						
8-16 inch square	0.250	6280	.....	..	....	..
9-16 inch square	0.316	6450	0.066	25	170	3
10-16 inch square	0.391	6970	0.075	23	520	8

It will be seen from the results in Table IX that there is an irregular increase in the holding power as the size of the rod is increased. Notice that with increments of 1-8-inch, the successive increments in the resistance are at first large, but with the last rod this increment suddenly falls to practically nothing. This drop in the increment is principally due to the tendency of the large rod to split the tie. The results with 1-16-inch increments do not differ materially from those in the first part of the table.

The deduction for Table IX is that the holding power will be increased as the size of the rod is increased, but that it is not expedient to use rods (or spikes) larger than 3-4 of an inch unless holes are bored for them.

F *Relation between the Depth of Penetration and Holding Power*

A series of experiments was made to determine the relation between the depth of penetration and the holding power. The results are given in Table X.

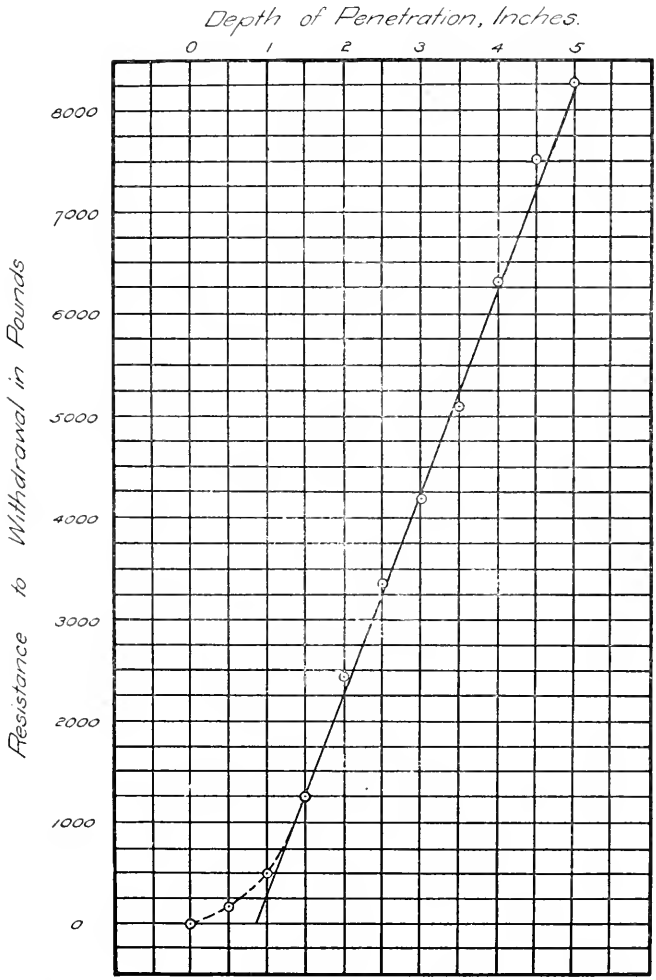
TABLE X

HOLDING POWER IN A WHITE OAK TIE WITH VARYING DEPTHS OF PENETRATION

Depth of Penetration	Resistance, Pounds					
	Test Number					Average
	1	2	3	4	5	
1-2 in.	150	150	140	160	170	150
1 in.	480	....	500	510	490	500
1 1-2 in.	1440	1000	1760	1320	950	1290
2 in.	2250	2250	2050	2900	2760	2450
2 1-2 in.	3430	3840	3050	2940	3570	3360
3 in.	3710	3800	4200	4220	4810	4210
3 1-2 in.	4760	5980	4210	4500	5860	5060
4 in.	5950	7190	6310	5850	6080	6270
4 1-2 in.	7510	7510	7720	7340	....	7520
5 in.	8380	9070	8540	7790	7900	8340

The spikes had a taper point approximately 1 inch long. Plate IV shows that the holding power varies directly with the penetration, not counting the taper point. It is impracticable to use a spike longer than 5 1-2 inches in a 6-inch tie, since a longer spike would either pass entirely through the tie or sliver it on the under side. In either case the fiber adjacent to the spike would quickly decay owing to the access of water. In a thicker tie, however, a longer spike could be used advantageously. The main precaution is to keep the spike from damaging the under surface of the tie. otherwise the longer the spike the greater the holding power.

PLATE IV



Ordinary Spikes.
Curve Illustrating Resistance to
Withdrawal for Various Depths of Penetration.

G Effect of the Point of the Spike on the Holding Power

There were three distinct types of points on the spikes,–blunt-point, chisel-point and bevel-point.

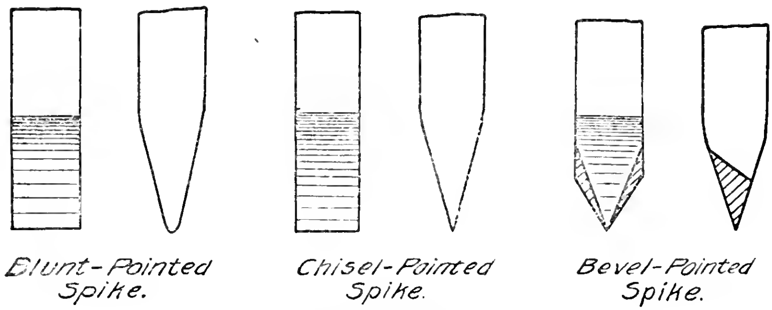
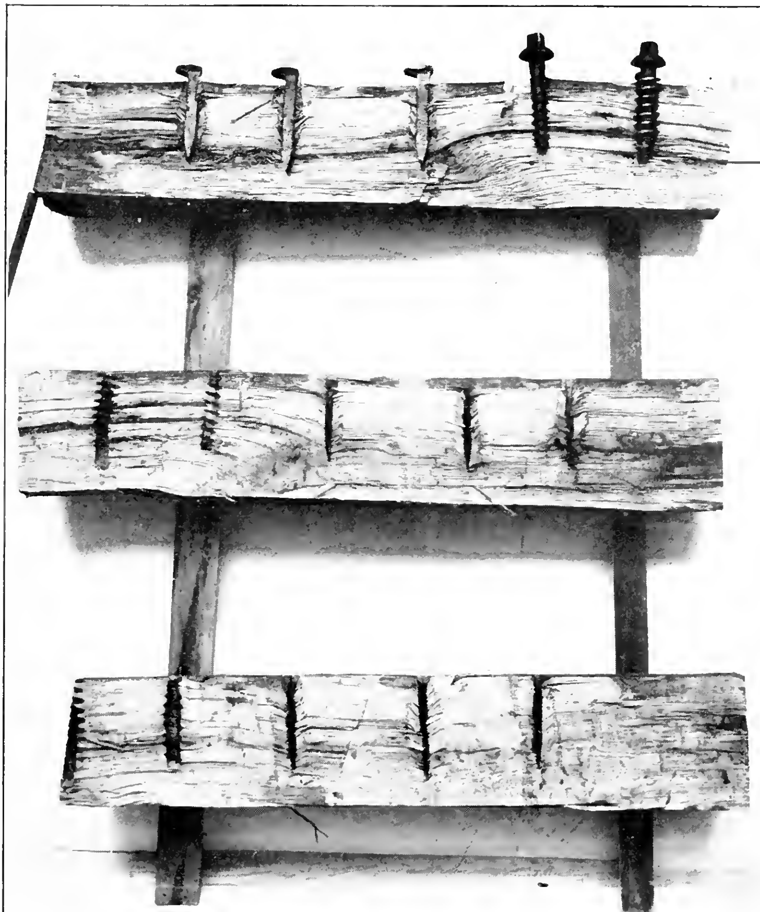


FIG. 1 FORMS OF POINTS OF SPIKES

The average results obtained with spikes having these types of points have been compiled from Table III, and are shown in Table XI. The average and relative resistances of each type of spike for all timbers are shown at the foot of the table. These averages show that both the blunt-pointed and the bevel-pointed spike are higher in holding power than the chisel-pointed spike. Since the average resistances of the blunt and the bevel-pointed spikes are practically the same, and since the blunt-pointed spike develops the highest resistance for the 1-8-inch and the 1-4-inch pull the greatest number of times, the blunt-pointed spike is first in point of efficiency, although the bevel-pointed spike is a close competitor under all conditions. The chisel-pointed spike is last.

The two upper figures of Plate V are the two halves of a red-oak tie showing the position of the fibers adjacent to the spike; and the lower figure is a portion of the other end of the same tie split after the spikes had been pulled out. The photograph was taken immediately after the tie had been split. The figures are too small to show details clearly, but an examination of the tie showed that the blunt-pointed spike disturbed more fiber than either the chisel or the bevel-pointed spikes, the last two disturbing about the same amount. The examination also showed that the blunt-pointed spike tore rather than cut the fibers, and deposited them in unequal bundles along its faces, while the chisel-pointed spike cut the fibers and deposited them quite uniformly both across and

PLATE V



Effect of Spikes in Displacing the Fibers of the Tie

TABLE XI

EFFECT OF THE FORM OF THE POINT OF THE SPIKE ON THE HOLDING POWER

Kind of Tie	No. of Spikes	Type of Point	Resistance in Pounds for 1-8 in. Pull		Resistance in Pounds for 1-4 in. Pull		Maximum Resistance	
			Pounds	Relative	Pounds	Relative	Pounds	Relative
Water Oak	33	Chisel	2780	100	5520	100	6540	100
	15	Bevel	3050	110	5440	98	6330	97
Black Oak	9	Blunt	3020	106	6890	121	8280	119
	18	Chisel	2850	100	5690	100	6930	100
	12	Bevel	2680	91	5560	98	6800	98
Red Oak	18	Blunt	2220	77	4400	82	5760	76
	21	Chisel	2880	100	5350	100	7630	100
	21	Bevel	3100	107	5580	104	7370	97
White Oak	10	Blunt	4080	117	7040	135	8760	123
	12	Chisel	3490	100	5190	100	7090	100
	6	Bevel	2990	86	5610	108	8010	113
Elm	21	Chisel	2150	100	5240	100	7710	100
	21	Bevel	2509	116	5740	109	7050	92
Beech	6	Blunt	2180	85	4670	84	9250	109
	6	Chisel	2570	100	5580	100	8470	100
	6	Bevel	3040	118	6190	111	7900	93
Chestnut	3	Blunt	2850	114	4950	162	5690	127
	3	Chisel	2490	100	3060	100	4470	100
	6	Bevel	3320	133	4130	135	5310	119
Loblolly Pine	3	Blunt	2860	84	3650	118	4020	97
	6	Chisel	3420	100	3390	100	4120	100
	9	Bevel	2800	82	5010	148	5520	134
Average for all		Blunt	2870	101	5340	112	6960	105
		Chisel	2840	100	4810	100	6610	100
Timbers		Bevel	2930	103	5490	114	6800	103

in front of each face. The bevel-pointed spike forced a majority of the fibers to the front face and toward the corners. The relatively high holding power of both the blunt and the bevel-pointed spikes is due to this unequal concentration of the fibers.

II Effect of Bored Holes on the Holding Power

A series of tests was made to study the effect of boring holes for the spike. The first step was to determine the proper size of the hole. Table XII shows the summary of a series of tests made at the University of Illinois in 1891* to determine the relationship between the holding power and the "drift".

TABLE XII

RESULTS OF EXPERIMENTS WITH SQUARE DRIFT-BOLTS IN PINE TIMBER

Size of Drift-Bolt	Size of Hole, inches	Drift, inches	Holding Power, Pounds	
			6-inch depth	Per inch depth
1 inch square	16-16	....	3972	662
1 inch square	15-16	1-16	4260	710
1 inch square	14-16	1-8	4660	777
1 inch square	13-16	3-16	4050	675

This table shows that with 1-inch square drift-bolts a drift of 1-8 of an inch gives a maximum holding power, but that a drift of 1-16 of an inch gives nearly as much resistance. It is not known that this relation holds with bolts less than 1-inch square, but the author assumed that this was sufficient reason for using a drift of 1-16 and 1-8 of an inch in this investigation, which conclusion is in accord with the usual railroad practice.

The second step was to determine the resistance to the different sized spikes in different kinds of ties. The detailed results for these experiments are given in Table XIII. Notice that the results are arranged according to the drift. The average results from Table XIII are shown in Table XIV along with the results from Table III for the same spike driven in the ordinary way.

The average resistances for all timbers, recorded at the foot of Table XIV, show that for a pull of 1-4 of an inch or less the spike driven into a bored hole develops higher holding power than one driven in the ordinary way. For a 1-4-inch pull or less the relative resistances show a marked increase in a majority of cases, but the maximum resistance for spikes driven into bored holes is usually the lowest.

* Technograph No. 5, 1891, University of Illinois

TABLE XIII

Holding Power of Ordinary Spikes in Bored Holes

Kind of Tie	Size of Spike, in. sq.	Diameter of Hole, inches	Resistance in Pounds for Pull of				Maximum Resistance	
			1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Pull, inches
			Hole 1-16 in. Smaller than Spike					
Water Oak	9-16	1-2	2330	3860	3660	3180	5740	5-16
			2050	3860	3970	3320	5730	3-8
			2020	6470	4740	4010	6750	5-16
			1660	4450	4090	3890	6460	5-16
			2500	6400	4120	3600	6400	1-4
			3250	3750	3440	3120	4940	3-16
			2390	4890	3930	3080	6740	5-16
		Av.	2310	4810	3990	3410	6110	
Black Oak	9-16	1-2	3460	6770	3570	2850	7190	5-16
			3000	7120	3810	3360	8190	5-16
			4590	6810	3550	3350	6810	1-4
			2670	6350	3850	3560	6350	1-4
			2910	6710	3390	2970	6710	1-4
			2260	6720	3810	3270	8630	1-2
		Av.	3150	6750	7310	3660	3230	
Red Oak	9-16	1-2	3970	6550	3500	3140	6830	5-16
			3920	6930	3250	3720	6930	1-4
			2180	5920	4590	3900	6990	5-16
			2830	6900	3770	3320	6900	1-4
			2660	4310	3440	2720	5320	5-16
			2870	5710	4090	3410	5710	1-4
			2900	6100	3380	3100	6100	1-4
			3950	6680	4690	4040	6680	1-4
			2700	7430	3410	3420	7480	1-4
			2680	7410	3950	3420	7410	1-4
		Av.	3070	6390	3810	3420	6640	
	5-8	9-16	3000	5380	3610	....	5380	1-4
			3300	5010	3360	....	5010	1-4
			3130	6240	3540	3510	6240	1-4
			2710	6530	4070	3600	7040	5-16
			2600	5460	5160	4170	6990	5-16
			2850	5810	4860	4400	8800	....
			3130	6800	6980	4950	9420	5-16
		Av.	2950	5890	4390	4140	6960	

TABLE XIII—*Continued*

Kind of Tie	Size of Spike, in. sq.	Diameter of Hole, inches	Resistance in Pounds for Pull of				Maximum Resistance	
			1-8 inch	1-4 inch	1-2 inch	3-4 inch	Pounds	Pull, inches
Ash	9-16	1-2	4080	7210	4720	3300	8180	5-16
			2510	6540	3360	3180	8380	5-16
			1980	4850	4380	4050	8830	7-16
			2850	5840	3220	2290	6180	5-16
			2530	5760	3510	2730	5760	1-4
		Av.	2790	6040	3840	3090	7460	
	5-8	9-16	3920	4700	3860	3280	6460	3-16
			2840	6300	4070	3600	6480	5-16
			1660	5100	5300	4370	8510	5-16
			2100	6340	5150	4540	8760	5-16
		Av.	2630	5610	4590	3950	7550	
Beech	9-16	1-2	2960	6820	3820	3790	7100	3-16
			2910	5710	4010	3550	7270	5-16
			2890	5610	3240	2850	5610	1-4
			2830	2900	2800	2690	6000	3-16
			3360	5450	2940	2620	5450	1-4
			3360	6610	3680	3210	6610	1-4
			3770	6780	3470	2890	8200	3-8
			2870	6930	4740	4360	6930	1-4
			3540	5110	5060	4010	7640	3-8
		Av.	3150	5770	3750	3330	6750	
Sweet Gum	9-16	1-2	2850	5840	3220	2290	6180	5-16
			2530	5760	3510	2730	5760	1-4
			2250	6210	4640	3570	7170	5-16
			2630	3940	3350	2870	4940	3-16
			2790	5220	4220	3680	6010	3-16
			2610	6300	3900	3370	6300	1-4
		Av.	2610	5550	3810	3080	6060	
	5-8	9-16	3030	3080	2740	2320	4370	3-16
			2620	5760	3560	2940	5760	1-4
			2850	3840	3290	2730	5500	3-16
		Av.	2830	4230	3200	2660	5210	

TABLE XIII—*Concluded*

Kind of Tie	Size of Spike, in. sq.	Diameter of Hole, inches	Resistance in Pounds for Pull of 1-8 inch	1-4 inch	1-2 inch	3-4 inch	Maximum Resistance Pounds	Pull, inches
			Hole 1-8 in. Smaller than Spike					
Red Oak	5-8	1-2	1800	5710	5000	4190	7270	5-16
			2340	6860	4490	3950	6860	1-4
			2630	5850	4010	3440	5850	1-4
			3170	4410	2570	2100	4410	1-4
			4070	3000	2600	2190	4410	3-16
			4720	4220	2550	2500	6030	3-16
		Av.	3270	5010	3540	3060	5800	
Beech	9-16	7-16	1340	4560	3530	3620	7080	3-8
			2540	5620	4720	4100	6920	5-16
			4000	4720	3000	2640	6000	3-16
			3560	7280	3800	3360	7280	1-4
			3580	5270	3800	3250	6940	3-16
			3240	6900	4020	3810	7830	5-16
			2510	6150	3710	3630	6150	1-4
			2290	4620	5410	4150	7950	7-16
			2790	6380	4630	3420	8230	5-16
			1900	3790	5010	4360	7660	7-16
		Av.	2180	5530	4160	3630	7200	
Sweet Gum	5-8	1-2	2400	...	2710	2320	3980	3-16
			2850	3180	2920	2540	4750	3-16
			2950	3700	3300	2240	5200	3-16
		Av.	2730	3430	2980	2370	4640	

TABLE XIV

AVERAGE RESISTANCE OF SPIKES WITH AND WITHOUT BORED HOLES

Kind of Tie	Size of Spike, in. sq.	No. of Spikes	How Driven	Resistance in Pounds for 1-8 in. Pull	Resistance in Pounds for 1-4 in. Pull	Resistance in Pounds for Maximum Resistance	Relative Resistance 1-8 in. Pull	Relative Resistance 1-4 in. Pull	Relative Resistance Maximum Resistance
			Drift 1-16 of an inch						
Water Oak	9-16	7	Hole	2310	4810	6110	78	85	92
		15	No Hole	2960	5660	6670	100	100	100
Black Oak	9-16	6	Hole	3300	6750	7310	110	122	113
		15	No Hole	2970	5320	6490	100	100	100
Red Oak	9-16	10	Hole	3070	6390	6640	111	112	97
		36	No Hole	3260	5450	6820	100	100	100
	5-8	7	Hole	2950	5890	6960	127	123	91
		21	No Hole	2310	4760	7660	100	100	100
Beech	9-16	9	Hole	3150	5770	6760	145	123	72
		9	No Hole	2180	4700	9410	100	100	100
Ash	9-16	5	Hole	2790	6040	7460	67	130	110
		6	No Hole	4150	4630	6810	100	100	100
Sweet Gum	9-16	6	Hole	2610	5550	6060	119	149	131
		6	No Hole	2190	3730	4610	100	100	100
	5-8	4	Hole	2830	4230	5210	82	95	96
		9	No Hole	3460	4450	5460	100	100	100
Av. for all Timbers	....	.....	Hole	2930	5680	6570	102	117	98
	....	....	No Hole	2880	4840	6740	100	100	100
			Drift 1-8 of an inch						
Red Oak	5-8	6	Hole	3270	5010	5800	141	105	75
		21	No Hole	2310	4760	7660	100	100	100
Beech	9-16	10	Hole	2780	5530	7200	122	118	77
		9	No Hole	2180	4700	9410	100	100	100
Sweet Gum	5-8	3	Hole	2730	34 30	4640	79	77	85
		9	No Hole	3460	4450	5460	100	100	100
Av. for all Timbers	....	....	Hole	2930	4660	6550	111	100	87
	....	....	No Hole	2650	4640	7510	100	100	100

As far as conclusions can be drawn from these experiments, the spike driven into a bored hole is superior to one driven in the ordinary way.

1 Effect upon the Holding Power of Re-driving the Spike

In practice, when the spike is pulled out of the tie a moderate distance, it is driven back, provided the hole is not greatly enlarged. If the hole is much enlarged the spike is driven at another point. This constant re-spiking rapidly ruins the tie. A series of tests was made to determine the effect upon the holding power of re-driving the spike. The average maximum holding power of the re-driven spikes is shown in Table XV along with the original maximum holding power of the same spike.

It will be seen that the holding power of the re-driven spike is very much less than that of the newly-driven spike. The resistance is affected so much in some woods as to make the practice of

TABLE XV

RELATIVE HOLDING POWER OF NEWLY-DRIVEN AND RE-DRIVEN SPIKES

Kind of Tie	No. of Spikes	Average Maximum Resistance, Pounds		Per cent of Original
		Original	After Re-driving	
Ash	6	8640	6490	75
Water Oak	6	8020	5760	72
Red Oak	6	8030	5230	65
Elm	6	7910	4840	61
Poplar	6	4920	3980	81
Sweet Gum	6	5040	4150	82

re-driving the spike a questionable procedure if the holding power alone is considered; but as the practice of re-driving the spike helps to lengthen the life of the tie, the practice can not be justly condemned so long as the holding power is not excessively reduced.

ART. 2 HOLDING POWER OF SCREW SPIKES WITHOUT LININGS

A series of tests was made to determine the holding power of screw spikes. The tests were conducted in the same manner as those with the ordinary spikes.

The screw spikes were received from the following companies: No. 1 from the Illinois Central Railroad Company; No. 2 from the American Iron and Steel Manufacturing Company, Scranton, Pennsylvania; No. 3 from the South Side Elevated Railroad Company, Chicago, Illinois; No. 4 from the Oliver Steel and Iron Company, Pittsburg, Pennsylvania: and No. 5 from the Pennsylvania Railroad Company.

A description of the different spikes is given in Table XVI.

TABLE XVI

DESCRIPTION OF SCREW SPIKES

Spike No.	Length, inches	Diameter of Core, inches	Projection of Thread, inches	Pitch, inches	Depth of Insertion, inches	Diameter of Bored Hole, inches
1	5	21-32	3-16	1-2	4 1-2	11-16
2	5	11-16	1-8	1-2	4 1-2	11-16
3	5 1-4	11-16	1-8	1-2	4 3-4	11-16
4	5 1-2	11-16	1-8	1-2	5	11-16
5	5	21-32	3-16	1-2	4 1-2	11-16

The shank or threaded portion of the spike was usually 7-8 of an inch in diameter, and approximately one inch of the upper portion of the core tapered from the diameter of the core to that of the shank. The hole bored for the spike was not reamed, and the result was a tight fit between the wood and the spike. This tight contact is gained in practice by the head of the spike bearing against the base of the rail. The spike was driven by means of a wrench, the thread cutting its own path. The number of screw spikes obtainable was not sufficient to make as long a series of tests as with the ordinary spikes.

A study of the results with this spike has been made to determine: (A) Relation between the depth of penetration and the holding power; (B) Relation between the holding power of the screw and of the ordinary spikes; and (C) Influence of certain details of the screw spike upon its holding power.

The detailed results of the tests with screw spikes are given in Table XVII, and the average results are shown in Plates II and III.

TABLE XVII

Detailed Record of Tests with Screw Spikes

Kind of Tie	No. of Tie	No. of Spike	No. of Test	Resistance in Pounds for a Pull of					Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	1 inch	Pounds	Distance Pulled, inches
Blue Ash	2	2	1	7350	10900	11650	6270	3370	13360	7-16
			2	5080	9930	13470	6010	3190	13470	1-2
			3	7520	11650	12300	6220	3030	12300	1-2
			Av.	6650	10830	12470	6160	3190	13040	1-2
	1	4	1	3320	7480	10840	6520	5000	10840	1-2
			2	3740	7570	9410	5940	4560	9410	1-2
			3	4350	9200	6800	4870	3260	9700	3-8
			Av.	3800	8080	9010	5780	3940	9980	1-2
Sweet Gum	3	2	1	3810	4940	4870	2420	1900	5980	7-16
			2	5790	7100	4900	3280	3770	7100	1-4
			3	4270	6030	4620	2820	3450	6590	3-8
			Av.	4620	6060	4790	2840	3040	6560	3-8
	3	4	1	5920	9000	6000	4000	2900	9720	7-16
			2	4550	7400	5600	3410	2300	8100	3-8
			3	4780	7120	5090	3290	1800	7870	3-8
			Av.	5080	7840	5560	3560	2330	8560	3-8
Water Oak	34	3	1	4820	10230	14530	9630	4600	14530	1-2
			2	4670	9170	12140	10000	6260	12640	5-8
			3	4680	7030	14360	9660	4490	14360	1-2
			Av.	4720	8810	13680	9800	5100	13840	7-16
	26	2	1	4110	8010	7190	3490	2150	9620	7-16
			2	3670	7420	7850	3970	2790	8900	3-8
			3	5270	7790	5190	3540	2600	8060	7-16
			Av.	4350	8290	6740	3660	2510	8860	7-16
Black Oak	16	3	1	5520	12370	16930	10720	6200	16930	1-2
			2	4860	11410	13100	7390	4050	14350	7-16
			3	4260	9870	9760	7690	3970	12160	3-8
			Av.	4880	11220	13260	8600	4740	14480	7-16
	23	2	1	5850	10290	9460	6600	4200	12500	3-8
			2	4910	10780	8590	6000	2500	12570	5-8
			3	1090	6370	10400	7100	6000	10400	1-2
			Av.	3950	9150	9380	6560	4230	11820	5-8

TABLE XVII—*Continued*

Kind of Tie	No. of Tie	No. of Spike	No. of Test	Resistance in Pounds for a Pull of					Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	1 inch	Pounds	Distance Pulled, inches
Red Oak	9	4	1	2720	7810	12720	7970	3710	12720	1-2
			2	6390	11440	11590	7050	3600	12770	3-8
			3	4240	9770	11130	9160	4970	11790	3-8
			Av.	4450	9670	11810	8060	4130	12430	3-8
	7	4	1	3940	9780	12780	9560	4880	13590	7-16
			2	7890	13860	14430	7990	4530	15200	3-8
			3	4220	9780	14800	12350	6500	14800	1-2
			Av.	5350	11140	12670	9960	6300	14860	7-16
Beech	36	2	1	2610	8400	8320	4170	....	14560	5-16
			2	8320	12370	10820	6130	....	13180	3-8
			3	5190	11880	11270	6880	....	14310	3-8
			Av.	5040	10850	10140	5730	....	14020	3-8
	14	3	1	6330	11980	10240	4480	3230	14550	7-16
			2	6130	12980	17360	9930	3900	17360	1-2
			3	8240	15620	14700	8900	5890	16450	7-16
			Av.	6900	13530	14000	7770	4340	16120	7-16
White Oak	31	4	1	3010	9340	8180	6390	4530	11630	7-16
			2	7950	12490	9390	5350	2880	13200	5-16
			3	8210	12080	7560	4950	3290	12740	5-16
			Av.	6390	11300	8380	5230	3570	12520	5-16
	31	3	1	5000	8290	5450	2960	....	8290	1-4
			2	4600	8030	6600	3340	....	8700	5-16
			3	5880	9370	....	....	....	10530	3-8
			Av.	5160	8560	5530	3150	....	9150	5-16
	32	3	1	6420	11300	16450	9590	4360	16450	1-2
			2	8590	14190	11370	5490	3190	15580	5-16
			3	4120	13000	Broke	....	....	13000	1-4
			Av.	6480	12830	13910	7040	3780	15010	3-8
Elm	10	3	1	4310	8290	14190	6340	2780	14190	1-2
			2	5040	10920	13200	7950	3100	14400	7-16
			3	4200	9130	13230	7350	3460	13230	1-2
			Av.	4520	9450	13540	7210	3110	13940	1-2

TABLE XVII—*Concluded*

Kind of Tie	No. of Tie	No. of Spike	No. of Test	Resistance in Pounds for a Pull of					Maximum Resistance	
				1-8 inch	1-4 inch	1-2 inch	3-4 inch	1 inch	Pounds	Distance Pulled, inches
Poplar	13	1	1	6090	11560	9920	4400	2420	11560	1-4
			2	5220	10400	11440	6450	3200	12740	7-16
			3	4570	9890	12400	7990	4000	14390	7-16
			Av.	5290	10280	11250	6260	3200	12890	7-16
	12	4	1	6830	11280	10080	5280	2340	12840	3-8
			2	3270	8650	9570	6350	3450	11610	7-16
			3	3700	7840	12480	7110	3360	12480	1-2
			Av.	4570	9260	10680	6250	3050	12310	7-16
	11	4	1	4130	7980	8000	4790	3300	10120	7-16
			2	2960	6200	8910	4820	2130	9610	7-16
			3	4760	7970	10130	7210	4480	10130	1-2
			Av.	3950	7380	9010	5610	3270	9960	7-16
	11	1	1	3450	6300	9340	5250	2940	9340	1-2
			2	3300	6550	8490	3860	1620	8490	1-2
			3	2640	5260	8060	2710	1520	8060	1-2
			Av.	3130	6040	8290	3940	2030	8290	1-2
Chestnut	40	4	1	5200	6950	6400	3340	....	7610	3-8
			2	2750	6210	8250	3800	....	8250	1-2
			3	3240	6260	6160	4580	....	7290	5-16
			Av.	3730	6480	6940	3910	....	7720	3-8
	40	1	1	3070	5460	5680	3570	1930	7010	7-16
			2	3960	3270	5310	2820	1140	6470	7-16
			3	3940	5630	5580	2510	1400	6300	7-16
			Av.	3660	5450	5520	2960	1490	6590	7-16
Loblolly Pine	20	1	1	5260	7610	5510	2670	1460	9340	3-8
			2	3840	6270	6210	3630	2120	7550	7-16
			3	4830	7780	7360	3060	2390	8190	3-8
			Av.	4640	7270	6390	3120	2320	8690	3-8
	39	1	1	6180	10220	7590	4070	1720	11840	3-8
			2	5350	8260	9060	5060	2460	11190	3-8
			3	....	...	8200	5520	3400	9850	7-16
			Av.	5820	9240	8280	4880	2530	10630	3-8

A Relation between Depth of Penetration and the Holding Power

A series of tests was made to determine the relation between the depth of penetration and the holding power of the screw spikes. The experiments consisted of pulling spikes driven to depths of 1, 2, 3, 4 and 5 inches into a beech tie, three spikes being used for each depth. The numerical results are shown in Table XVIII, and their averages are shown graphically in Plate VI together with some additional matter which is shown for the sake of comparison.

TABLE XVIII

RESULTS OBTAINED FROM EXPERIMENTS ON DEPTH OF PENETRATION

Test Number	Resistance in Pounds for a Penetration of				
	1 inch	2 inches	3 inches	4 inches	5 inches
1	2770	4560	9610	13100	17360
2	2760	6000	10000	14330	17500
3	2790	4940	8490	13330	16840
Av.	2770	5170	9360	13590	17230

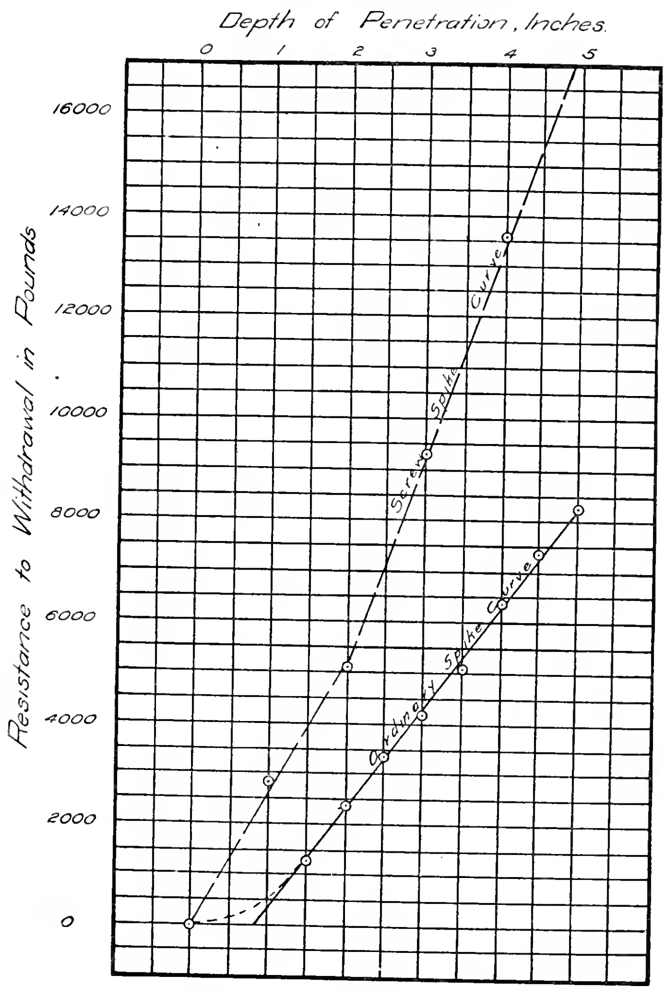
The results in Plate VI can be quite closely represented by two intersecting straight lines. The probabilities are that the actual resistances would be more nearly represented if the two straight lines were joined by a short curve near their intersection. Only the upper portion of the diagram is of interest, since penetrations of less than four inches should never be used, at least on heavy traffic railroads, the only roads likely to use screw spikes.

The diagram shows that the resistance varies directly with the depth of penetration.

B Relative Holding Power of Screw Spikes and Ordinary Spikes

Table XIX has been prepared from Table XVII and from Table III, to determine the relation between the holding power of the screw spike and that of the ordinary spike. As previously stated, the ordinary spikes were driven into the tie to a uniform depth of 5 inches, while the screw spikes, being of different lengths, necessarily were inserted to unequal depths. On account of the relation existing between the depth of penetration and the holding power, the resistance for the screw spikes, shown in Table XIX, is based upon a penetration of 5 inches.

PLATE VI



Curves Illustrating Resistance to Withdrawal of the Screw and Ordinary Spikes for Various Depths of Penetration

From Table XIX it will be seen that the holding power of the screw spike is always greater than that of the ordinary spike, and that the relation between the two varies in the several timbers. For a pull of 1-4 of an inch in the hard woods the holding power of the screw spike is from 167 to 221 per cent of that of the ordinary spike, and in the soft woods the range is from 117 to 258 per cent; or the average gain in the hard woods is 76 per cent, and in the soft woods 98 per cent. It is interesting to note that the resistances in the several timbers for the 1-8-inch pull with the screw spike are in eight out of eleven instances nearly the same as, or greater than, the resistances for the 1-4-inch pull with the ordinary spike. This signifies that the screw spike is about twice as efficient as the ordinary spike for a pull of 1-4 of an inch or less. The curve in Plates II and III show graphically the relative efficiency of the two forms of spikes with some information to be referred to later.

C Effect of Certain Details of the Screw Spike upon Its Holding Power

In countries where the screw spike is extensively used it has been perfected in detail until it nearly fulfills the requirements of practice. In North America the screw spike will probably be the successor to the ordinary spike, and it may again be necessary to adjust the details to suit local conditions. Therefore a few observations on the relation of some of the details of this spike to its holding power come within the scope of this paper. The details to be discussed are the diameter of the core, the projection and pitch of the thread and the length of the thread. These details being interdependent will be discussed collectively.

The soft steel from which the screw spike is made has an ultimate strength of about 66,000 pounds per square inch, so that the tensile strength of a spike 11-16 of an inch in diameter is approximately 24,000 pounds. The ultimate compressive resistance across the grain of well-seasoned white oak is about 4,000 pounds per square inch, and experiments demonstrate that the thread of the spike in compacting the wood fibers increases the resistance about 40 per cent.* Therefore, taking 5,600 pounds as the ultimate compressive strength of compacted white oak, and taking 17 3-4 inches and 1-8 of an inch respectively as the length and projection of the

*Bulletin No. 50, U. S. Dept. of Agriculture.

TABLE XIX

Relative Holding Power of the Screw Spike and of the Ordinary Spike in Several Timbers

Kind of Tie	Kind of Spike	Resistance in Pounds for			Relative Resistances		
		1-8-in. Pull	1-4-in. Pull	Max. Resist.	1-8-in. Pull	1-4-in. Pull	Max. Resist.
Water Oak	Ordinary	2870	5730	6780	100	100	100
	Screw	4888	9180	12190	170	160	179
Black Oak	Ordinary	2910	5890	7230	100	100	100
	Screw	4760	10420	14110	164	177	203
Red Oak	Ordinary	2950	5350	7730	100	100	100
	Screw	4900	10400	13560	166	194	176
White Oak	Ordinary	3510	5950	7870	100	100	100
	Screw	6250	11900	12630	178	200	188
Ash	Ordinary	3570	5200	7730	100	100	100
	Screw	5700	10470	12760	162	200	165
Beech	Ordinary	2600	5490	8840	100	100	100
	Screw	6450	13140	16230	248	221	238
Elm	Ordinary	2380	5580	7500	100	100	100
	Screw	5120	10090	13690	215	181	183
Poplar	Ordinary	2830	5290	5670	100	100	100
	Screw	3880	6210	7490	137	117	132
Chestnut	Ordinary	2850	4070	5200	100	100	100
	Screw	3690	6340	8700	129	155	167
Sweet Gum	Ordinary	3230	4120	5300	100	100	100
	Screw	5430	7710	8280	167	162	156
Loblolly Pine	Ordinary	2920	3500	4300	100	100	100
	Screw	5750	9050	10620	197	258	247

thread on the 5-inch spike, and making no allowance for frictional resistance between the core of the spike and the wood, the theoretical resistance would be

5,600 x 17 3-4 inches x 1-8 inches=12,430 pounds.

The average actual resistance obtained in white oak ties as shown in Table XIX is 12,630 pounds which agrees closely with the theoretical resistance. The tensile strength of the screw spike is

about 12,000 pounds greater than the maximum resistance of white oak, which difference is greater than necessary and indicates an uneconomical use of metal in the spike. Since the ties tested are representative of American practice, there is no apparent reason for not having the ultimate strength of the two materials in contact more nearly equal than at present, and by some slight change in the detail of the spike this could readily be accomplished. Three ways in which the ultimate strength of the materials may be made more nearly equal are: (1) increase in length of threaded portion; (2) increase in projection of thread, the length and the diameter of the core remaining the same; (3) increase in projection of thread at the expense of the core, the length remaining the same. The pitch is assumed to be 1-2 inch in all cases, since it has been found in practice that this pitch gives better results than either a greater or smaller pitch.*

(1) The length of the thread on the 5-inch spike is 17 3-4 inches and the width is 1-8 of an inch; therefore, the bearing area is 2.22 square inches. If the spike is made 6 inches long two convolutions of the thread will be added, the bearing area will become 2.71 square inches, and the holding power will be increased from 12,630 pounds to 15,180 pounds. This leaves a difference of only 8,900 pounds between the ultimate strength of the wood and that of the spike.

(2) If the length of the spike and the diameter of the core are not changed, and if the projection of the thread is increased 1-32 of an inch, the total resistance would amount to 15,510 pounds, leaving the ultimate strength of the spike only 8,500 pounds greater than that of the wood.

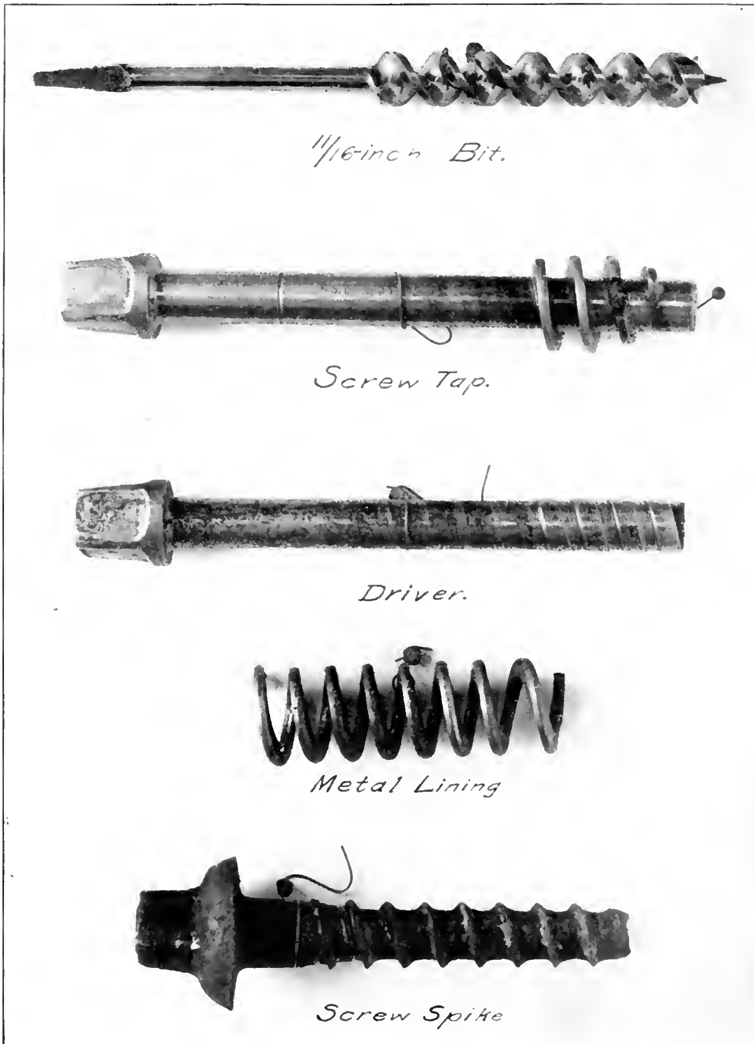
(3) If the length of the threaded portion of the spike remains unchanged and if the projection of the thread is increased 1-32 of an inch at the expense of the core, the maximum resistance would amount to 15,510 pounds, while the ultimate strength of the spike would be reduced to 20,200 pounds.

The diameter of the shank of the spike would have to be increased with some of the changes in the detail of the lower portion, and when the resistance to lateral displacement is taken into account, we see that this change also would be beneficial.

The conclusion is that the screw spike in its present form is

*Bulletin No. 50, U. S. Dept. of Agriculture.

PLATE VII



SCREW SPIKES AND TOOLS FOR INSERTING THEM

about twice as efficient as the ordinary spike; and that this efficiency could be increased by some slight change in the detail of the screw spike.

Art. 3 Holding Power of Screw Spikes with Helical Linings

A few experiments were made with screw spikes having helical linings. On account of the small number of linings obtainable the tests were limited; as this lining, being a foreign invention, is not yet used by the railroads of this country except for experimental purposes. The tests were still further limited since the linings could not be used a second time; and further since all of the linings could not be driven successfully, as the friction between the metal and the wood sometimes caused the driver to loosen its hold, which could not be regained even after carefully following printed instructions. This accounts for the use of only two linings in some of the timber. The linings together with a set of special tools for inserting them in the tie were furnished by Mr. Robert Trimble, Chief Engineer Maintenance of Way, Pennsylvania Lines, (see Plate VII).

The linings were made by Mr. J. Thiollier of Paris, France, and are described by him as being 0.33 inch by 0.17 inch in section, and also as being of the class which he calls P. M. or small sized linings. They were 4 inches long with a 1-2-inch pitch. The total diameter was 1 5-16 inches, the diameter inside of the spiral band slightly over 11-16 of an inch, and the thickness and width of the metal band 1-8 and 1-4 of an inch, respectively. The linings were evidently designed to be used with the screw spike of the French Eastern Railway, No. 1, Table XVI, and hence they were tested with this spike only.

The method of fixing the lining in place was as follows: A hole having the same diameter as the core of the spike was bored in the tie; the hole was tapped, and the lining inserted by means of special tools designed for the purpose; the spike was inserted in the usual manner.

The detailed results of these tests are shown in Table XX, and the average results are shown graphically in Plates II and III. The relative holding power of the several kinds of spikes in different timbers is shown in Table XXI. The results of this table and the diagrams in Plates II and III show that in hard woods

the resistances for a 1-8-inch pull are usually greater for the spike and lining than for the naked screw spike, but for pulls greater than 1-8 of an inch the reverse is true. In soft woods the spike and lining gave greater resistances than the naked screw spike except in sweet gum. The lower resistance in the hard woods is accounted for by the fact that the spike begins to move before the lining, and the fibers, being hard, are bent slightly upward so that the bearing surfaces of the wood and the spike are only partially in contact. Moreover, the fibers probably slip over the rounded edge of the lining, which tends to lower the resistance. In the soft woods more than in the hard woods, the fibers mash together as the spike is pulled out, consequently the bearing surfaces of the wood and the spike have full contact and the resistance is greater than with the naked screw spike.

In justice to Mr. Thiollier it is only right to say that he claims no more for the P. M. lining than is set forth in these experiments. He says that the P. M. lining will offer no more resistance than a naked screw spike. The principal claims for the P. M. lining are that it can be placed on the track without removing either the rail or the tie, and that it forms an advantageous substitute for the square wooden dowel used on some railways.

As a repair measure this lining is of doubtful value, for it extends only about 1-8 of an inch beyond the thread of the spike; and when the spike has been pulled even a small distance the adjacent wood is badly damaged, so that the wood which remains after the hole is tapped for the lining can offer but slight resistance. Moreover, it is not certain that the extreme fibers reached by the lining are not somewhat affected, hence it would be better to ream the hole, cutting out all damaged wood and to introduce a threaded hard wood dowel, or to use a lining of larger size.

The writer claims that the use of the small lining is impracticable for the following reasons: (1) It is designed to be put in place with the tie in the track; (2) The lining cannot always be inserted into the wood to its full length by means of hand tools, even with utmost precaution; (3) At best the holding power is not increased to any marked degree over that of the naked screw spike; and (4) The labor involved is more than double that required to drive the naked screw spike, and the cost is increased.

TABLE XX

RESISTANCE OF SCREW SPIKES WITH HELICAL LININGS

Kind of Tie	Tie No.	No. of Tests	Resistance in Pounds for Pull of					Maximum Resistance	
			1-8 in.	1-4 in.	1-2 in.	3-4 in.	1 in.	Pounds	Pull, in.
Ash	1	1	8410	11380	10150	7570	6480	12160	1-4
		2	5830	8670	9410	6590	5630	10500	3-8
		3	5670	8070	7930	4690	4200	8750	3-8
		Av.	6640	9370	9160	6280	5440	10470	3-8
Sweet Gum	3	1	6010	9100	7750	5380	5150	9510	1-4
		2	4830	6440	7650	6270	4380	7970	3-8
		3	4270	6250	8600	6130	4410	8600	1-2
		Av.	5030	7260	8000	5930	4650	8690	3-8
Water Oak	26	1	3420	7100	11080	8290	8740	11080	1-2
		2	2970	6460	12080	9250	9170	12080	1-2
		Av.	3190	6780	11580	8780	8960	11580	1-2
White Oak	32	1	5810	10740	8420	6890	7120	12900	3-8
		2	7070	11020	6650	6170	6340	11020	1-4
		Av.	6440	10880	7530	6530	6750	11960	3-8
Black Oak	23	1	5960	11130	9810	8560	7520	12550	3-8
		2	5420	9710	10770	8470	7960	12460	3-8
		Av.	5690	10420	10290	8510	7740	12500	3-8
Beech		1	10830	10120	8070	7320	5390	10830	1-8
		2	8610	11600	11850	10350	6280	13480	3-8
		Av.	9720	10860	9960	8830	5830	12150	1-4
Poplar	11	1	3970	8860	9900	5880	5306	9920	3-8
		2	4080	9470	10550	5940	5110	11140	3-8
		3	3670	8260	9910	6030	5250	9910	1-2
		Av.	3910	8860	10120	5950	3220	10320	3-8
Chestnut		1	7020	9600	8230	6920	6120	9770	3-8
		2	5750	7010	8890	8180	6730	8890	1-2
		3	6300	7240	9280	7660	6860	9280	1-2
		Av.	6390	7950	8810	7590	6900	9150	1-2

TABLE XXI

RELATIVE HOLDING POWER OF THE ORDINARY SPIKE, THE SCREW SPIKE, AND THE SCREW SPIKE WITH HELICAL LINING IN SEVERAL TIMBERS

Kind of Tie	Kind of Spike	Resistance in Pounds for			Relative Resistance		
		1-8-in. Pull	1-4-in. Pull	Max. Resist.	1-8-in. Pull	1-4-in. Pull	Max. Resist.
White Oak	Ordinary	3510	5950	7870	100	100	100
	Screw*	6250	11900	12630	178	200	188
	Lining	6440	10880	11960	183	183	152
Water Oak	Ordinary	2870	5730	6780	100	100	100
	Screw*	4880	9180	12190	170	160	179
	Lining	3190	6780	11580	111	118	171
Black Oak	Ordinary	2910	5890	7230	100	100	100
	Screw*	4760	10420	14110	164	177	203
	Lining	5690	10420	12500	195	177	173
Ash	Ordinary	3570	5200	7730	100	100	100
	Screw*	5700	10470	12760	162	200	165
	Lining	6640	9370	10470	186	180	135
Beech	Ordinary	2600	5490	8840	100	100	100
	Screw*	6450	13140	16230	248	221	238
	Lining	9720	10860	12150	373	198	138
Poplar	Ordinary	2830	5290	5670	100	100	100
	Screw*	3850	6210	7490	137	117	132
	Lining	3910	8860	10320	138	162	182
Chestnut	Ordinary	2850	4070	5200	100	100	100
	Screw*	3690	6340	8700	129	155	167
	Lining	6390	7950	9150	224	195	176
Sweet Gum	Ordinary	3230	4120	5300	100	100	100
	Screw*	5430	7710	8280	167	162	156
	Lining	5030	7260	8690	136	176	164

* Screw spike with helical lining.

The * belongs after "Lining."

PLATE VIII

Impact Apparatus

PART II RESISTANCE TO LATERAL DISPLACEMENT

The railroad spike is subjected not only to a direct pull by the undulation of the rail, but also to a horizontal thrust due to the lateral movement of the rail. On roads having a large amount of curvature the lateral resistance is of more importance than that of direct pull.

To determine the amount of the resistance to lateral displacement which is developed by various forms of spikes the writer made a series of tests in which the lateral thrust was produced by the blows of a heavy hammer. The hammer consisted of a cast-iron weight suspended by a wooden rod from the joists of the floor above.

The place in which the apparatus was used was such that a good photograph could not be taken. Plate VIII is a view of the apparatus set up in a light suitable for photographing. All essential features are correctly represented. Fastened to the joists were metal strips upon which the knife edges of the rocking arm rested. These strips were 6 feet long, and were notched along the entire upper edge to permit the placing of the rocking arm in different positions. The length of the suspending rod was 9 feet.

The weight of the hammer was 100 lb. and the distance through which it was allowed to fall was 1 1-2 feet, so that the amount of the impact for each blow was 150 ft.-lb. The hammer delivered its blow on the end of a tool-steel bar which projected beyond the end of the tie, the other end of the bar being shaped to fit under the head of the spike.

The spikes used in this series of tests were 9-16 inch and 5-8 inch ordinary spikes and screw spikes. Each spike was subjected to five blows and the displacement produced by each blow was carefully measured. Usually four or five spikes of each kind were tested, but when there was much lack of uniformity in the results a larger number were tested.

All of the spikes were bent to a curve, the central point of which was about 1 1-2 inches below the surface of the tie. The ordinary spikes were pulled from the tie a short distance, but the thread of the screw spikes gripped the wood so as to prevent the spike from being pulled out even a perceptible amount.

Art. 3 Lateral Resistance of Ordinary Spikes

The detailed results of the experiments with ordinary spikes are given in Table XXII and the average movement of the spike for each of the several blows is shown in Table XXIII. The average total movement of the 5-8 inch spikes in the first seven timbers was 0.65 inch, and that of the 9-16 inch spikes was 0.75 inch. In the last four timbers the average total movement of the 5-8 inch spikes was 0.74 inch, and that of the 9-16 inch spikes was 0.94 inch.

The total deflection of the 9-16 inch spikes was usually sufficient to allow a rail to clear the head of the spike if it were overturned. The corresponding movement of the 5-8 inch spikes was not usually sufficient to allow a like clearance, although it was considerably more than would be allowed in practice.

The first blow is of more importance than the succeeding blows in testing the efficiency of a spike. While the distances through which the different sized spikes were deflected by the first blow differ but a small amount, this difference is sufficient to show that the deflection is less for the 5-8 inch spikes than for the 9-16 inch.

These results, together with the fact that the 5-8 inch spikes were bent less by the impact than the 9-16 inch spikes, indicate that the 5-8 inch spike is more efficient in resisting lateral displacement than the 9-16 inch spike.

Art. 4 Lateral Resistance of Screw Spikes

The method of determining the lateral resistance of screw spikes was the same as that used for ordinary spikes. The results for this set of tests are given in Table XXIV. The screw spikes used were all practically alike except that they were of various lengths. In making the tests the spikes were used indiscriminately, but since they were not all of the same length some tests were made to determine the effect of impact upon spikes which were driven into the tie to different depths. The spikes used for the latter tests were all of the same make, and were cut to lengths of 3, 3 1-2, 4, 4 1-2 and 5 inches, and were all driven into a single kind of timber. The results of these tests are shown in Table XXV. While the results for the 4- and 4 1-2-inch spikes are the same, the

TABLE XXII

DETAILED RESULTS OF IMPACT TESTS OF ORDINARY SPIKES

Kind of Tie	Size of Spike, in. sq.	Total Lateral Movement of Spikes in Inches				
		Number of Blows				
		1	2	3	4	5
White Oak	9-16	0.27	0.35	0.48	0.65	0.81
		.18	.35	.56	.67	.73
		.10	.22	.33	.45	.54
		.30	.35	.50	.52	.60
		.21	.35	.60	.74	.93
	Av.	0.21	0.32	0.49	0.61	0.70
	5-8	0.11	0.20	0.26	0.30	0.39
		.15	.30	.41	.50	.57
		.19	.36	.50	.60	.68
		.21	.36	.49	.65	.74
		.20	.34	.42	.50	.57
	Av.	0.17	0.31	0.42	0.51	0.59
Water Oak	9-16	0.23	0.34	0.52	0.60	0.75
		.20	.33	.56	.73	.88
		.14	.42	.53	.68	.75
		.20	.35	.48	.54	.65
		.19	.39	.63	.72	.78
	Av.	0.19	0.37	0.54	0.65	0.76
	5-8	0.12	0.25	0.36	0.48	0.55
		.20	.37	.54	.63	.69
		.15	.25	.31	.39	.50
		.19	.28	.43	.51	.65
		.20	.37	.53	.65	.69
	Av.	0.17	.30	0.43	0.53	0.61
Black Oak	9-16	0.25	0.40	0.56	0.70	0.75
		.13	.30	.41	.58	.72
		.16	.32	.49	.58	.70
		.24	.44	.62	.71	.80
		.23	.35	.56	.65	.69
		.26	.39	.59	.67	.78
	Av.	0.21	0.37	0.54	0.65	0.71
Black Oak	5-8	0.23	0.38	0.50	0.58	0.65
		.17	.30	.42	.53	.64
		.17	.35	.50	.61	.77
		.15	.32	.40	.49	.55
		.11	.26	.37	.41	.45
		.22	.35	.50	.59	.65
	Av.	0.17	0.33	0.45	0.53	0.62

TABLE XXII—*Continued*

Kind of Tie	Size of Spike, in. sq.	Total Lateral Movement of Spikes in Inches				
		Number of Blows				
		1	2	3	4	5
Red Oak	9-16	0.21	0.35	0.51	0.61	0.73
		.19	.30	.46	.57	.75
		.20	.37	.55	.64	.77
		.22	.41	.49	.61	.72
	Av.	0.21	0.36	0.50	0.61	0.74
	5-8	0.12	0.21	0.32	0.42	0.49
		.15	.24	.34	.43	.50
		.12	.25	.35	.49	.53
		.18	.42	.55	.72	.85
	Av.	0.14	0.28	0.39	0.52	0.60
Ash	9-16	0.24	0.45	.057	0.68	0.80
		.24	.43	.53	.65	.74
		.20	.33	.52	.65	.75
		.25	.41	.60	.72	.83
	Av.	0.23	0.41	0.56	0.68	0.78
	5-8	0.19	0.37	0.55	0.73	0.84
		.19	.33	.48	.64	.75
		.18	.31	.44	.60	.69
		.15	.30	.39	.54	.63
	Av.	0.18	0.33	0.47	0.63	0.73
Elm	9-16	0.22	0.33	0.50	0.67	0.78
		.21	.30	.39	.56	.70
		.25	.37	.49	.58	.66
		.18	.30	.43	.54	.67
	Av.	0.22	0.33	0.45	0.59	0.70
	5-8	0.20	0.38	0.50	0.61	0.71
		.21	.35	.48	.60	.72
		.20	.35	.49	.61	.70
		.21	.32	.44	.55	.66
	Av.	0.21	0.35	0.48	0.59	0.70
Beech	9-16	0.28	0.30	0.58	0.72	0.87
		.26	.46	.57	.75	.86
		.21	.32	.53	.65	.75
		.30	.54	.63	.71	.89
		.19	.37	.55	.70	.80
		.27	.46	.61	.72	.86
	Av.	0.25	0.41	0.58	0.71	0.84

TABLE XXII—*Continued*

Kind of Tie	Size of Spike, in. sq.	Total Lateral Movement of Spikes in Inches				
		Number of Blows				
		1	2	3	4	5
	5-8	0.15	0.23	0.33	0.46	0.53
		.13	.20	.29	.41	.49
		.16	.27	.36	.49	.58
		.12	.26	.43	.50	.57
		.12	.30	.37	.46	.62
		.14	.25	.31	.39	.50
	Av.	0.14	0.25	0.35	0.45	0.55
Poplar	9-16	0.27	0.41	0.59	0.75	0.88
		.22	.40	.54	.67	.74
		.30	.45	.60	.68	....
		.27	.41	.54	.75	.84
		.27	.40	.52	.61	.76
	Av.	0.27	0.41	0.56	0.69	0.81
	5-8	0.10	0.29	0.41	0.50	0.63
		.16	.28	.41	.51	.60
		.20	.39	.50	.66	.75
		.17	.39	.39	.46	.57
	Av.	0.16	0.34	0.43	0.53	0.64
Chestnut	9-16	0.35	0.65	0.90	1.06	1.40
		.35	.60	.80	.97	1.10
		.35	.60	.90	1.12	1.35
		.31	.62	.91	1.01	1.19
		.29	.52	.75	.93	1.18
		.30	.50	.73	.93	1.19
	Av.	0.32	0.58	0.83	1.09	1.23
	5-8	0.17	0.40	0.60	0.78	0.85
		.10	.30	.67	.88	1.05
		.27	.45	.63	.80	.92
		.25	.48	.70	.91	1.03
		.24	.40	.57	.75	.90
		.28	.42	.53	.65	.84
	Av.	0.22	0.41	0.61	0.79	.93
Sweet Gum	9-16	0.29	0.51	0.60	0.78	0.95
		.23	.40	.66	.75	.88
		.30	.51	.67	.75	.92
		.31	.54	.72	.97	1.10
	Av.	0.28	0.49	0.66	0.81	0.96

TABLE XXII—*Concluded*

Kind of Tie	Size of Spike, in. sq.	Total Lateral Movement of Spikes in Inches				
		Number of Blows				
		1	2	3	4	5
Sweet Gum	5-8	0.14	0.28	0.45	0.62	0.78
		.18	.35	.54	.62	.75
		.16	.33	.46	.62	.70
		.14	.38	.42	.50	.61
	Av.	0.16	0.34	0.47	0.59	0.17
Loblolly Pine	9-16	0.22	0.33	0.50	0.61	0.70
		.23	.38	.65	.76	.81
		.12	.23	.35	.42	.50
		.24	.37	.58	.71	.88
		.26	.42	.53	.70	.75
		.23	.45	.64	.72	.77
	Av.	0.22	0.36	0.54	0.65	0.74
	5-8	0.16	0.30	0.40	0.50	0.65
		.17	.42	.63	.72	.85
		.17	.22	.30	.51	.55
		.15	.23	.40	.52	.59
		.23	.38	.46	.61	.71
		.12	.19	.29	.36	.41
		.23	.39	.53	.68	.78
	Av.	0.18	0.30	0.43	0.56	0.65

averages in the last column of the table show that the amount of the lateral movement decreases as the depth of penetration increases. Also, the difference between the deflections of the 4-, 4 1-2-, and 5-inch spikes is practically negligible, but for shorter lengths the difference in the deflections becomes greater.

Table XXVI gives the lateral movement of the screw spikes for each of the several blows for which the total movements were given in Table XXIV. The number of spikes used in each kind of timber was usually three; but in case there was considerable variation in the results, more spikes were tested. By a study of this table the effect of impact upon screw spikes in different kinds of timber may be determined.

TABLE XXIII

LATERAL MOVEMENT OF ORDINARY SPIKES FOR EACH BLOW

Kind of Tie	Size of Spike, in. sq.	Movement for Each of the Several Blows, inches					Average Movement, inches
		1	2	3	4	5	
White Oak	9-16	0.21	0.11	0.17	0.12	0.09	0.136
	5-8	0.17	0.14	0.11	0.09	0.08	0.118
Water Oak	9-16	0.19	0.18	0.17	0.11	0.11	0.152
	5-8	0.17	0.13	0.13	0.10	0.08	0.122
Black Oak	9-16	0.21	0.16	0.17	0.11	0.06	0.142
	5-8	0.17	0.16	0.12	0.08	0.09	0.124
Red Oak	9-16	0.21	0.15	0.14	0.11	0.13	0.148
	5-8	0.14	0.14	0.11	0.14	0.08	0.122
Ash	9-16	0.23	0.18	0.15	0.12	0.10	0.156
	5-8	0.18	0.15	0.14	0.16	0.10	0.146
Elm	9-16	0.22	0.11	0.12	0.13	0.11	0.138
	5-8	0.21	0.14	0.13	0.11	0.11	0.140
Beech	9-16	0.25	0.16	0.17	0.13	0.13	0.168
	5-8	0.14	0.11	0.10	0.10	0.10	0.110
Poplar	9-16	0.27	0.14	0.15	0.14	0.12	0.164
	5-8	0.16	0.18	0.09	0.10	0.11	0.128
Chestnut	9-16	0.32	0.26	0.25	0.17	0.23	0.246
	5-8	0.22	0.19	0.20	0.18	0.14	0.186
Sweet Gum	9-16	0.28	0.21	0.17	0.15	0.15	0.192
	5-8	0.16	0.18	0.13	0.12	0.12	0.142
Loblolly Pine	9-16	0.22	0.14	0.18	0.11	0.04	0.148
	5-8	0.18	0.12	0.13	0.13	0.09	0.128

TABLE XXIV

DETAILED RESULTS OF IMPACT TESTS OF SCREW SPIKES

Kind of Tie		Total Lateral Movement of Spike, in Inches				
		Number of Blows				
		1	2	3	4	5
White Oak		0.09	0.16	0.23	0.30	0.38
		.10	.20	.24	.32	.41
		.07	.14	.21	.28	.40
	Av.	0.09	0.17	0.23	0.30	0.40
Black Oak		0.11	0.21	0.26	0.36	0.40
		.10	.19	.25	.33	.44
		.11	.18	.24	.31	.42
	Av.	0.11	0.19	0.25	0.33	0.42
Water Oak		0.09	0.13	0.22	0.33	0.42
		.11	.17	.23	.34	.45
		.08	.18	.26	.35	.41
	Av.	0.09	0.16	0.24	0.34	0.43
Red Oak		0.12	0.21	0.35	0.45	0.54
		.11	.20	.34	.44	.52
		.17	.23	.33	.46	.52
	Av.	0.13	0.21	0.34	0.45	0.53
Ash		0.17	0.23	0.34	0.47	0.54
		.18	.27	.35	.46	.55
		.12	.25	.33	.45	.53
	Av.	0.16	0.25	0.34	0.46	0.54
Elm		0.11	0.30	0.38	0.48	0.56
		.12	.22	.37	.49	.53
		.21	.40	.58	.85	.96
		.25	.40	.52	.63	.75
	Av.	0.17	0.33	0.46	0.61	0.70
Beech		0.10	0.18	0.23	0.28	0.36
		.11	.18	.26	.31	.37
		.12	.19	.25	.32	.42
		.16	.28	.38	.49	.58
		.17	.31	.52	.58	.65
		.20	.40	.52	.60	.68
	Av.	0.14	0.26	0.36	0.43	0.51

TABLE XXIV—*Concluded*

Kind of Tie		Total Lateral Movement of Spike, in Inches				
		Number of Blows				
		1	2	3	4	5
Poplar		0.09	0.16	0.32	0.60	0.78
		.10	.16	.27	.40	.61
		.09	.15	.34	.39	.49
		.19	.35	.44	.61	.78
		.18	.40	.53	.62	.75
		.17	.27	.40	.63	.71
		.16	.30	.39	.51	.62
	Av.	0.17	0.24	0.38	0.54	0.67
Chestnut		0.16	0.23	0.38	0.43	0.50
		.13	.22	.37	.52	.56
		.12	.24	.33	.42	.51
		.20	.31	.39	.51	.59
		.19	.28	.39	.48	.65
	Av.	0.16	0.26	0.37	0.47	0.56
Sweet Gum		0.20	0.38	0.52	0.68	0.78
		.26	.46	.60	.71	.79
		.30	.48	.51	.74	.88
		.18	.32	.40	.49	.61
		.25	.38	.47	.59	.68
	Av.	0.24	0.40	0.50	0.64	0.74
Loblolly Pine		0.20	0.41	0.62	0.72	0.88
		.21	.39	.58	.69	.78
		.21	.32	.48	.64	.81
		.23	.37	.56	.66	.80
	Av.	0.21	0.37	0.56	0.68	0.82

Table XXVII is given to facilitate the comparison of the relative lateral resistance of ordinary and screw spikes. The data were collected from Tables XXIII and XXVI. The average total deflection of the screw spike in the first seven timbers is 0.50 inch which is 0.15 inch less than that of the 5-8-inch ordinary spike and 0.25 inch less than that of the 9-16-inch ordinary spike. In the

TABLE XXV

RELATION BETWEEN THE DEPTH OF PENETRATION AND THE RESISTANCE TO LATERAL DISPLACEMENT

Depth of Insertion	Deflection in Inches — Number of Blows 1	2	3	4	5	Average for Five Blows
3 in.	0.24	0.46	0.64	0.78	0.87	
	.22	.41	.55	.69	.84	
	.24	.43	.67	.76	.98	
Av.	0.23	0.43	0.62	0.73	0.90	0.582
3 1-2 in.	0.24	0.46	0.62	0.77	0.80	
	.24	.39	.53	.69	.80	
	.19	.34	.49	.63	.74	
Av.	0.22	0.40	0.55	0.70	0.78	0.530
4 in.	.20	0.39	0.49	0.60	0.71	
	.21	.40	.57	.63	.77	
	.23	.33	.57	.62	.72	
Av.	0.21	0.37	0.54	0.62	0.73	0.494
4 1-2 in.	0.24	0.30	0.50	0.65	0.74	
	.20	.34	.53	.68	.73	
	.22	.36	.54	.62	.79	
Av.	0.22	0.33	0.52	0.65	0.75	0.494
5 in.	0.22	0.38	0.49	0.61	0.71	
	.23	.40	.55	.67	.75	
	.15	.34	.48	.57	.69	
Av.	0.20	0.34	0.51	0.62	0.72	0.478

last four kinds of timber the average total deflection of the screw spike was 0.70 inch, which is practically the same as that of the 5-8-inch ordinary spike, but which is 0.24 inch less than that of 9-16-inch common spike. The results in the last two columns of Table XXVII show that the screw spike is superior to the 9-16-inch ordinary spike in all but two kinds of timber, and that the screw spike has a higher efficiency than the 5-8-inch ordinary spike in all but three kinds of timber.

TABLE XXVI

LATERAL MOVEMENT OF THE SCREW SPIKE FOR EACH BLOW

Kind of Tie	Movement for Each of the Several Blows					Average Movement, inches
	1	2	3	4	5	
White Oak	0.09	0.08	0.05	0.07	0.10	0.078
Black Oak	0.11	0.08	0.06	0.07	0.09	0.082
Water Oak	0.09	0.07	0.08	0.10	0.09	0.086
Red Oak	0.13	0.08	0.13	0.12	0.08	0.108
Ash	0.16	0.09	0.09	0.12	0.08	0.108
Elm	0.17	0.16	0.13	0.15	0.09	0.140
Beech	0.14	0.12	0.10	0.07	0.08	0.102
Poplar	0.17	0.07	0.12	0.16	0.13	0.130
Chestnut	0.16	0.10	0.11	0.10	0.09	0.132
Sweet Gum	0.24	0.16	0.10	0.14	0.10	0.148
Loblolly Pine	0.21	0.13	0.19	0.12	0.14	0.154

The last two columns in Table XXVII show that the ordinary spike was usually displaced more than the screw spike by each blow. This should be expected since the common spike was smaller in cross section than the screw spike, and also since the latter had better bond with the wood. While the use of the screw spike is recommended to the American railroads, it is thought that the practice of Bavarian railroads could be followed to advantage. These roads have adopted the use of the screw spike on the gage side of the rail to resist overturning, but use two square spikes on the outside to resist lateral movement. This practice has been found to give very beneficial results. The figures in the last two columns of Table XXVII show that the lateral resistance of two ordinary spikes is considerably more than that of one screw spike, and therefore if two spikes are considered as resisting the impact instead of one, the results will be in favor of the ordinary spikes. Not only is this true, but the first cost for spikes would be reduced, since the screw spike costs about four cents at

TABLE XXVII

RELATIVE LATERAL DISPLACEMENT OF ORDINARY AND SCREW SPIKES

Kind of Tie	Movement of Ordinary Spikes		Average Movement of Screw Spike, inches	Average Movement of Ordinary Spikes in Terms of per cent of Movement of Screw Spike	
	9-16 in.	5-8 in.		9-16 in.	5-8 in.
White Oak	0.136	0.118	0.078	175	152
Black Oak	0.152	0.122	0.082	186	149
Water Oak	0.142	0.124	0.086	165	145
Red Oak	0.148	0.122	0.108	137	115
Ash	0.156	0.146	0.108	144	135
Elm	0.138	0.140	0.140	99	100
Beech	0.168	0.110	0.102	165	108
Poplar	0.164	0.128	0.130	126	99
Chestnut	0.246	0.186	0.132	186	141
Sweet Gum	0.192	0.142	0.148	129	96
Loblolly Pine	0.148	0.128	0.154	96	83

the present time, whereas the ordinary spike costs much less. The maintenance cost of either form of spike is almost negligible.

An item of interest which is properly beyond the limits of this article is that of the ninety screw spikes used in making these tests only two were broken. One was broken under a tension of 14,000 pounds, the break being caused by an incipient crack just under the head of the spike. The other spike broke under the fourth blow of the hammer, this break being due to uncombined graphite in the metal. As the spikes were obtained from different sources, and were of different manufacture, it is thought that the test was sufficiently severe to show that the screw spike, as manufactured at present, will successfully withstand the shocks of passing trains. As the spikes were used several times during the tests, the percentage of spikes broken is very low.

Summary of Results

(1) The maximum resistance to direct pull varies from 6,000 to 14,000 pounds for screw spikes, from 3,000 to 8,000 pounds for ordinary spikes when driven into untreated timbers, and from 4,000 to 9,000 pounds for ordinary spikes when driven into treated timbers.

(2) The direct pull required to withdraw ordinary spikes 1-8-inch varies from 2,000 to 3,500 pounds for untreated timbers, and from 2,500 to 3,500 pounds for treated timbers.

(3) The direct pull required to withdraw ordinary spikes 1-4-inch varies from 3,000 to 5,400 pounds for untreated timbers and from 3,800 to 5,900 pounds for treated timbers.

(4) Timbers having loose fiber structures have lower resistances to direct pull than timbers having compact fiber structures.

(5) The amount of withdrawal which must occur for ordinary spikes to develop the maximum resistance is less for soft woods than for hard woods.

(6) Spikes driven into treated timber offer a greater resistance to direct pull than spikes in untreated timbers, and the difference between this resistance for treated and untreated timbers is greater for soft woods than for hard woods.

(7) The difference in the resistance to direct pull for the different sized spikes in use (9-16 inch, 19-32 inch, and 5-8-inch) is very small.

(8) The resistance of ordinary spikes to direct pull varies directly as the depth of penetration, neglecting the tapering point.

(9) Blunt-pointed and bevel-pointed spikes have a slightly greater resistance to direct pull than chisel-pointed spikes.

(10) For withdrawals less than 1-4 inch, ordinary spikes which are driven into bored holes have a little greater resistance to direct pull than spikes driven in the ordinary way.

(11) The resistance to direct pull for re-driven spikes is from 60 to 80 per cent of the resistance of newly driven spikes.

(12) The efficiency of screw spikes to resist withdrawal is nearly twice as great as that of common spikes.

(13) The resistance of 5-8-inch spikes to lateral displacement is slightly greater than that of 9-16-inch spikes.

(14) The resistance to lateral displacement increases with

the depth of penetration, but the increase is negligible for depths of penetration greater than 4 inches.

(15) Screw spikes are more efficient than ordinary spikes in resisting lateral displacement.

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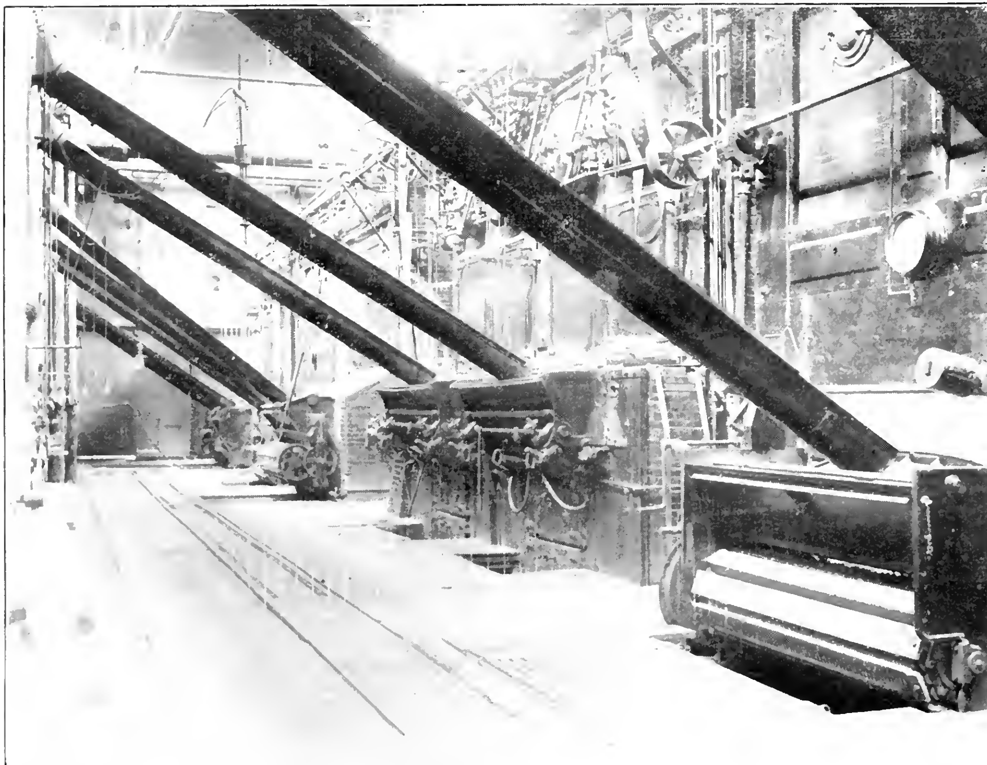

View in Central Heating Station University of Illinois

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 7 AUGUST 1906

FUEL TESTS WITH ILLINOIS COALS

BY

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During the last ten years a considerable number of boiler trials have been made at the University of Illinois. Many of these have been made under the boilers in the power plant of the University. Still other trials have been made with boilers in use at the plants in neighboring cities. In some instances experts representing several special stoker and furnace companies have been present at these trials and operated the devices in which they were interested. For the most part, however, the tests have been made in order to instruct students in the usual methods of boiler testing, and the boilers themselves have been operated under such usual conditions as happened to obtain. In some of the earlier tests all of the data relating to the heating value of the coals were not obtained, and for such tests several items depending on these values are necessarily omitted. While in most cases these tests have not been made with the object of making a comparison of coals or of appliances, nevertheless, it has seemed wise to publish the results obtained and also to exhibit these results side by side as they apply to various forms of furnaces, types of boilers or kinds of coal. It is entirely probable that the results obtained are equal to those generally obtained under the varying conditions of plants using Illinois coals. Many more boiler trials have been

made than are here reported, but only such are included in this report as appear to be free from any indications of errors in methods or results. For the purpose of this bulletin all of the results of the tests have been carefully rechecked.

The work of the department of Applied Chemistry has not only supplemented the work relating to boiler trials by furnishing the composition and heating value of the coals used in these trials, but it has also examined and tested a large number of Illinois coals not yet tested under boilers. In connection with this subject this department has perfected several new devices very useful to chemists and engineers, designed for making the ordinary determinations of the heating values and composition of coals. The Parr calorimeter, one of these devices, has found ready sale among the operators of many of the power plants of the country as well as among the consulting chemists and fuel experts. It is expected that a separate bulletin will soon be published setting forth in detail many of the new methods which have been developed by this department, and giving the complete results of its investigations relating to Illinois coals. It is hoped that the tables of the chemical composition and heating values of Illinois coals, which form a part of this bulletin, will furnish engineers and manufacturers with useful information in this important field.

With the above somewhat general statement in explanation of the character of this bulletin, it may now be advisable to refer more in detail to the special features which are intended to be brought out in the following pages.

Boiler Testing

For many years engineers have been making "boiler tests" with the object of finding out how many pounds of water in the boiler could be evaporated with one pound of coal. In order that the results of the tests might be comparable, it became evident that some common method of making tests should be agreed upon and also that the tests made should be reported in a uniform manner. A committee of the American Society of Mechanical Engineers recommended to that Society in 1899 a method of testing boilers and also a method of reporting such tests. These methods have been largely used since their recommendation at that time. The many expert engineers who are to-day so familiar with these methods will probably not be interested in the pages

immediately following. Having in mind the owners and operators of power plants as well as manufacturers and young technical students, it has seemed worth while to present somewhat in detail the following subjects:

(1) Observations to be made during a boiler trial.

(2) Appliances used during a boiler trial.

(3) Form of report, methods of operation and explanation of computations.

I OBSERVATIONS TO BE MADE DURING A BOILER TRIAL

In the report of the committee of the American Society of Mechanical Engineers,[1] 1899, on the revision of the standard code for conducting steam boiler trials, two forms of report are submitted, a Complete Form and a Short Form. These are both shown in Section III, page 21. The observations necessary to complete either of these forms are given in Table I. An explanation of some of the methods used in obtaining these observations and the forms used in recording them follow.

COAL, WATER AND ASH

The two fundamental points to be determined in every test of a steam boiler or furnace, regardless of the special or specific purpose of such test, are the pounds of water evaporated by the boiler and the pounds of fuel necessary to produce such evaporation. To determine these two points it is necessary to know the number of pounds of water fed into the boiler and the pounds of fuel fed into the furnace. The possibility of an error in either throws doubt upon all the indications of the test. Each item, therefore, should be ascertained in a manner that proves its own correctness, and the records must be such that if errors are made, they will be clearly exposed.

Coal.—The weight of the coal is best obtained by means of a barrow or car with a capacity of 500 pounds. The car should be loaded uniformly each time and weighed on platform scales in front of the furnace. The total weight and the time of weighing should be recorded in the log. From the car the coal should be fired directly into the furnace and the weight of the separate

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1 See Trans. A. S. M. E. Vol. XXI, p. 34.

TABLE I

OBSERVATIONS TO BE MADE DURING A BOILER TRIAL

Short Trial	Standard Trial	Observations
1	1	Weight of water fed to boiler
2	2	Weight of coal as fired (sample)
3	3	Weight of ash and refuse (sample)
4	4	Moisture in coal
5	5	Steam pressure by gage
6	6	Force of draft: between damper and boiler
7	7	in furnace
	8	in ash-pit
8	9	Temperature: of feed water entering boiler
9	10	of escaping gases from boiler
	11	of external air
	12	of fire-room
	13	of steam
	14	of feed water entering heater
	15	of feed water entering economizer
	16	of escaping gases from economizer
	17	of gases in furnace
10	18	Moisture in steam by calorimeter
	19	Analysis of flue gases
	20	Smoke observations
	21	Average thickness of fire, intervals of firing

charges and time of firing entered in the log. After the entire car-load of coal has been fired, the weight of the empty car and the time should be recorded. The sum of the separate charges must then be equal to the difference in weight of the car when loaded and empty. A convenient form for recording the coal fired is shown in Form I. From each car-load of coal fired an average sample of coal should be taken for moisture determination and chemical analysis. The sample of course must be taken before the coal is weighed and should be about two per cent of every car-load, or about ten pounds. At the end of the test these samples from the different cars are mixed, pounded into small sizes, and then quartered until enough is left to fill a two-quart jar. The jar should then be sealed, to prevent loss of moisture, and sent to the chemist.

Feed Water.—The water fed to the boiler should be both weighed and measured, as dependence upon measuring alone will introduce errors due to uneven filling and variations in temperature; for the latter, however, corrections may be made. The measuring tank or preferably two tanks should be set on scales in such a position that the water can be delivered directly into the suction or settling tank as shown in Fig. 1. The measuring tanks should be filled and emptied alternately, the time of each weighing to be noted when the tank is empty, the tanks being designated as No. 1 and No. 2. In no case should a simple tally be recorded for

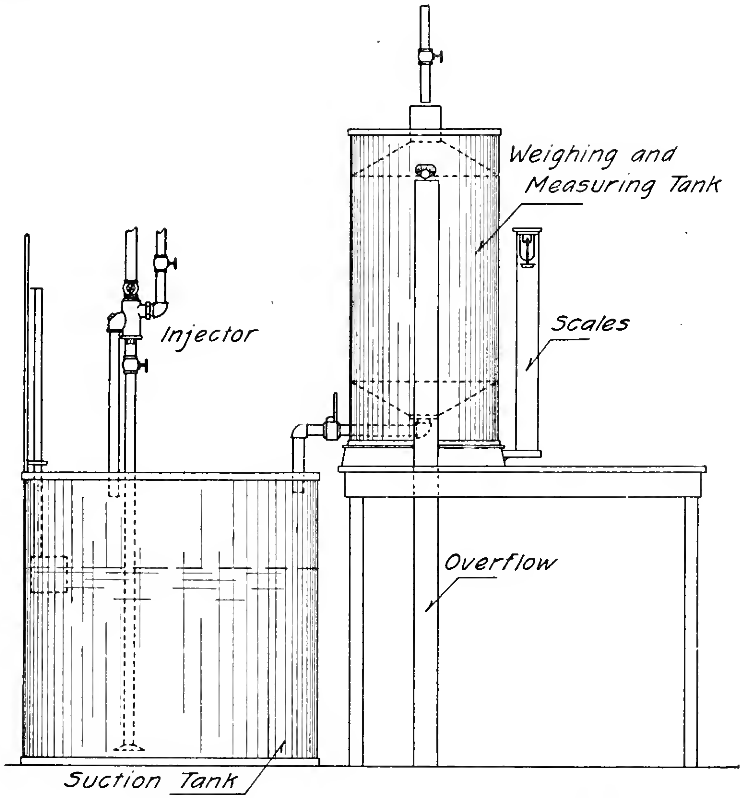

FIG. 1 ARRANGEMENT OF TANKS AND SCALE FOR MEASURING FEED-WATER FED TO BOILER

each tankful, as the liability of error is thereby increased. When the boiler tested is of small capacity, one weighing tank will be sufficient. A convenient form for recording the feed water measurements is shown in Form II.

To guard against the loss of all data, due to accidents, it is best to have coincident records of the water and coal fed to boiler. For this reason it is well to have a float in the suction or settling tank, and each time an entire car-load of coal has been fired, the time on the feed water log should be recorded, also the height of water in the boiler and in the settling tank. This will also provide a check on the uniformity of operations.

Ash.—The ashes and refuse should be weighed dry. The time of each raking of the fire and cleaning of the ash-pit and the weight

FORM I

LOG OF BOILER TRIAL NO ....

Made at........................

Date........................... By.....................

Boiler No...................... Fireman...... ....

COAL SHEET

TIME	COAL DELIVERED TO SCALES POUNDS	COAL ON SCALES AFTER EACH FIRING POUNDS	COAL FIRED EACH TIME POUNDS	FUEL
				Moist coal consumed, pounds
				Moisture in coal, per cent
				Dry coal consumed, pounds
				Wood consumed, pounds
				Coal equivalent of wood (=wood x.4) lb
				Total dry coal consumed including wood equivalent, pounds
				Total dry refuse, pounds
				Total dry refuse, per cent
				Total combustible
				DESCRIPTION OF FUEL
				Commercial Name
				Commercial size
				Lumps, per cent
				Small coal, per cent
				Slack, per cent
				Appearance of coal
				Record the times when fires are cleaned

FORM II

LOG OF BOILER TRIAL NO...........

Made at.........................

Date............................ By.....................

Boiler No...................... . Fireman................

FEED WATER SHEET

TIME	WATER DELIVERED TO FEED TANK POUNDS	TEMP. OF WATER IN TANK	TIME	WATER DELIVERED TO FEED TANK POUNDS	TEMP. OF WATER IN TANK	REMARKS
						Test began at
						o'clock M.
						Date
						Test closed at
						o'clock M.
						Date.

FORM III

LOG OF BOILER TRIAL NO........ ...

Made at........................

Date............... .... By ....

Boiler No...................... Fireman... ....

TIME	PRESSURES			TEMPERATURES					HEIGHT OF WATER IN GLASS GAGE	REMARKS
	STEAM GAGE	DRAFT GAGE	BAROMETER	BOILER ROOM	EXTERNAL AIR	FLUE GASES	FEED WATER	STEAM		
....	....	....	....	....	....	....	....	....	....	Test began at ....
....	....	....	....	....	....	....	....	....	....	o'clock M. ....
....	....	....	....	....	....	....	....	....	....	Date, ...
....	....	....	....	....	....	....	....	....	....	Test closed at ....
....	....	....	....	....	....	....	....	....	....	o'clock M. ....
....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....
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....	....	....	....	....	....	....	....	....	....	....
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....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....	....

FORM IV

LOG OF BOILER TRIAL NO.... ......

Made at........................

Date............... ....   By. ....

Boiler No.... ....   Fireman.................

TIME	CALORIMETER			DRAFT			HEIGHT OF WATER IN TANK	HEIGHT OF WATER IN GLASS GAGE	REMARKS
	GAGE PRESSURE	STEAM DISCHARGE OR CALORIMETER TEMP.	WATER SEPARATED OR CALORIMETER PRESSURE	BETWEEN DAMPER AND BOILER	IN FURNACE	IN ASH PIT			
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....
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....	....	....	....	....	....	....	....	....	....
....	....	....	....	....	....	....	....	....	....

FORM V

LOG OF BOILER TRIAL NO...........

Made at........................

Date............................ By.........................

Boiler No...................... Fireman................

FLUE-GAS SHEET

TIME	CO_2	O_2	CO	HYDROGEN AND HYDROCARBONS	TOTAL	REMARKS
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
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....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....
....	....	....	....	....	....	....

of ash removed should be recorded in the same log as the weight of coal, Form I. A representative sample of ash should be taken at every cleaning and saved in order to determine the principal characteristics of the ash, a proximate analysis giving the actual amount of incombustible material being made of each sample.

General Observations

Although the main points to be determined in a boiler trial are the weight of water evaporated and the amount of fuel burned, the general observations of pressures, temperatures, etc., under which this evaporation takes place and which tend to secure the accuracy of these two measurements must not be overlooked. It is necessary that all available data be obtained and recorded in the log for use in making comparisons. The value of the observation will depend primarily upon its correctness and the greatest care should be exercised in obtaining and recording observations. Too often the observer is guided by personal opinion and former readings, and the value of the observation as an indication of some specific occurrence is entirely lost.

All general observations should, as nearly as possible, be taken at the same instant, the exact time in all cases being recorded in the log. As a rule all observations should be recorded in duplicate, this being necessary especially where several persons are concerned with the results. Duplicates are easily obtained by placing carbon copying paper below the original log. The duplicates are then obtained as the results are originally recorded. Forms for recording the general observations are shown in Forms III to V.

For convenience it is best to have the log sheets tacked to a board, which may be suspended on the wall at some convenient point. This avoids the accumulation of dust and dirt when the sheets are lying around unattached in a horizontal position.

Sufficient time should elapse between temperature measurements if only one thermometer serves for taking several observations, in order to allow the thermometer to assume the new temperature. Where the range of temperature is large, however, this should never be practised, and it will be preferable in most cases to take only the most important of the readings, being certain of its correctness.

Determinations of the moisture in the steam are necessary to make corrections in the amount of water evaporated, and should be made at regular intervals and entered in the log.

The analysis of the flue gases is important as it indicates to some extent the progress of combustion in the furnace. Notwithstanding, the general use of this analysis is still very limited, although in some instances a record of the CO_2 in the flue gases is regularly kept. The value of the analysis consists in its being an indication of the amount of excess air being used. The flue gas to be analyzed should be an average sample taken continuously over a considerable period of time. This is necessary as the composition of the gases varies from minute to minute. Under ordinary conditions an analysis every half-hour is sufficient; special readings, however, may be taken more often. The apparatus for sampling will be explained in the following section.

II Appliances Used During A Boiler Trial

Since the corrections to be applied to the weights of fuel and water fed to the boiler are dependent on the general observations, the appliances necessary for their determination must be considered. The correctness of the observations will depend primarily on the instruments used and their location. In the following paragraphs these are discussed to some extent.

Description of Appliances

A list of the apparatus necessary to take the observations given in Section I is shown in Table II. The apparatus required

TABLE II

Appliances for Observations Given in Table I

Short Trial	Standard Trial	Appliances
1	1	Measuring and suction tanks for measuring water
2	2	Platform scales for weighing water
3	3	Car or barrow for handling coal
4	4	Platform scales for weighing coal
5	5	Standard calibrated steam gage
6	6	Draft gages, U tubes or otherwise
7	7	Thermometers according to observations made
8	8	Flue gas thermometer
	9	Pyrometer for furnace temperatures
9	10	Throttling or separating calorimeter
	11	Orsat apparatus for flue gas analysis
	12	Smoke charts

in the determination of the weights of coal and water was discussed in the previous section and needs no explanation other than that the scales used should be calibrated so that a correction may be applied if necessary. The suction tank should also be calibrated so that the contents of the tank are known for all positions of the float.

For measurement of the steam pressure an ordinary steam gage calibrated by comparison with a standard gage or other means will suffice. A good recording steam gage carefully adjusted and compared at frequent intervals with the steam gage provides a good check. Various forms of draft gages are used to determine the draft pressure. The ordinary U tube is the most common form and gives very satisfactory results. A gage of the type shown in Fig. 2 has been extensively used at the University and gives results which can be read with greater accuracy than the U tube.

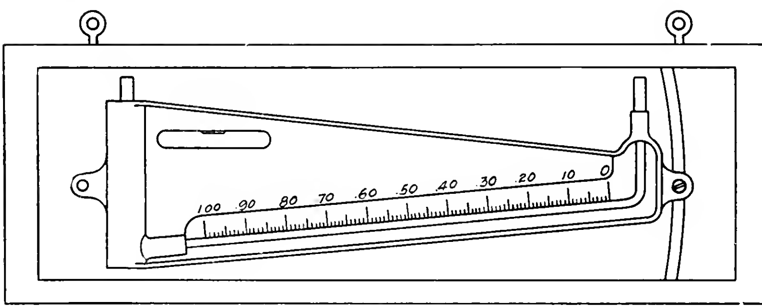


FIG. 2 DRAFT GAGE

In the choice of thermometers care should be taken that the range of readings will fall within that of the thermometer. Where thermometers are likely to be handled constantly, a metal casing is desirable. Where temperatures within a pipe are required, as in steam or water pipes, thermometer cups, as shown in Fig. 3 will need to be used.

Either mercury or a heavy cylinder oil may be used in these cups; the former, however, is preferable both for cleanliness and accuracy. For the measurement of flue gas temperatures a special mercury thermometer is used, reading up to 1000° F., with nitrogen compressed above the mercury.

The thermometer should be calibrated from time to time to insure its correctness. The location of the thermometer will be discussed in the following section.

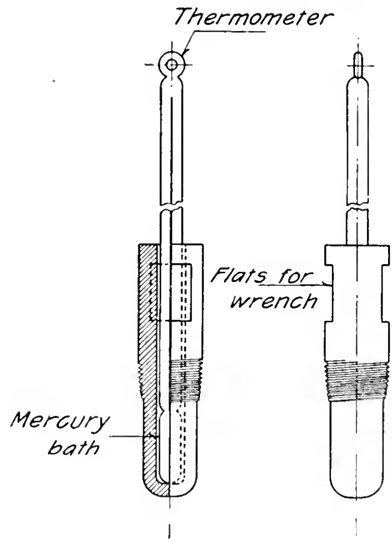


FIG. 3 THERMOMETER CUP, USED TO OBTAIN TEMPERATURES WITHIN A PIPE

The measurement of furnace temperatures is very difficult, and no especial form of pyrometer has proved to be entirely satisfactory. The Wanner optical pyrometer is being used at the Government Coal-Testing Plant at St. Louis, and seems to be giving fair results.

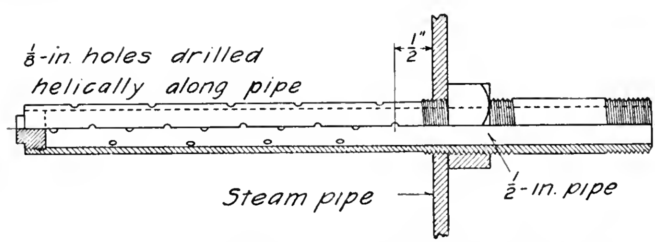


FIG. 4 SAMPLING NOZZLE FOR STEAM CALORIMETER

For determining the moisture in the steam, as long as the moisture remains below three per cent, any one of several forms of calorimeters may be used with good results. Above this point, all calorimeters are inaccurate, owing to the inability to obtain an average sample of the steam. The sampling nozzle, Fig. 4, should be made of ½-in. pipe, and should extend across the diameter of

the steam pipe to within half an inch of the opposite side, being closed at the end, and perforated with not less than twenty $\frac{1}{8}$-in. holes equally distributed along and around its cylindrical surface, but none of these holes should be nearer than $\frac{1}{2}$ inch to the inner side of the steam pipe. The calorimeter and pipe leading to it should be well covered with felt. When a separating calorimeter with attached gage for determining the amount of steam passing through the calorimeter is used, such gage should be calibrated by taking readings over twenty minutes in length, and condensing the steam passing through the calorimeter during that time, the weight of condensed steam being compared with the indication on the gage. This should be repeated for the entire range of the gage. Superheating should be determined by means of a thermometer placed in a mercury well, inserted in the steam pipe.

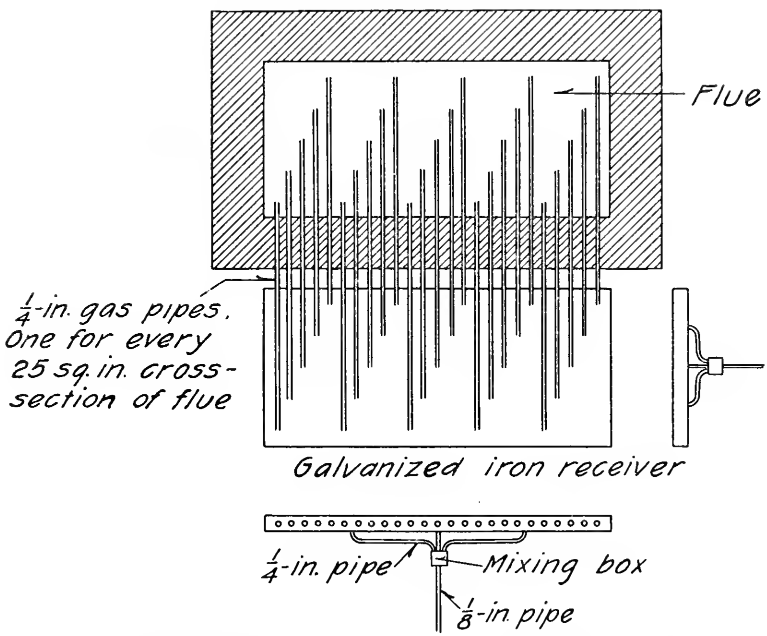


FIG. 5 FLUE GAS SAMPLER, ADVISED IN THE A. S. M. E. STANDARD CODE FOR CONDUCTING STEAM BOILER TRIALS

For determining the composition of the flue gases a sampling tube for drawing the sample of gas from the flue is necessary, also apparatus for analyzing the gas. There has been a great diversity of opinion regarding the method to be used in obtaining the

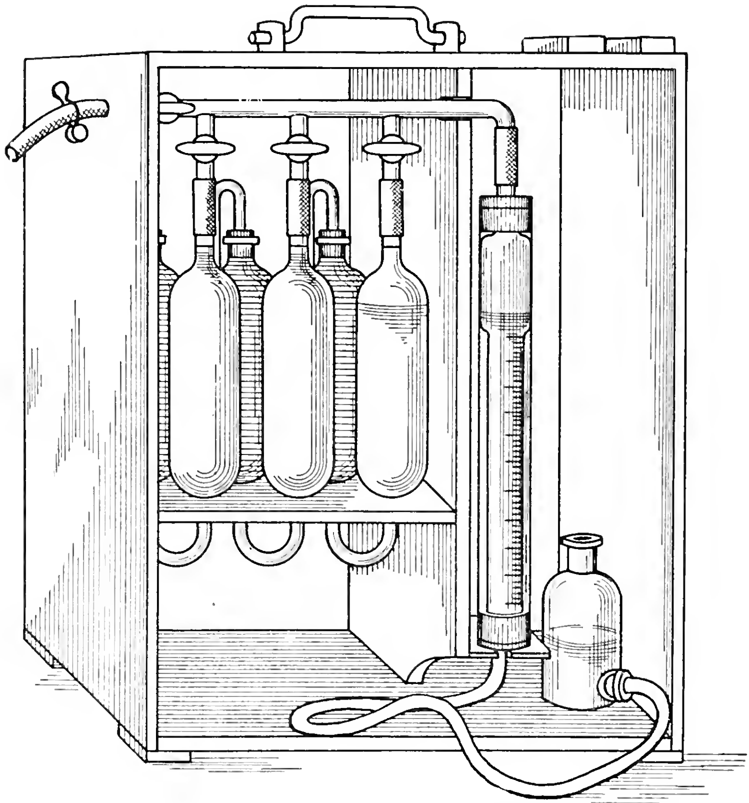


FIG. 6 ORSAT APPARATUS FOR ANALYZING FLUE GAS

sample, due probably to the varying conditions in different boiler settings and at different points in the same flue. In the trials carried on by the United States Geological Survey at St. Louis, both the sampler advised in the A. S. M. E. code, Fig. 5, and an ordinary pipe closed at the end and perforated with holes equally spaced along its entire length have been used. The results indicate the advisability of using the latter, and it has been adopted for use in all future trials. To get a uniform flow through all the perforations, they are made of such size and number that the sum of the areas of the perforations is less than the cross sectional area of the sampling tube. The Orsat apparatus is the one mostly used for analyzing the flue gases, as it is simple in operation, and with a little care gives reliable results. To insure the

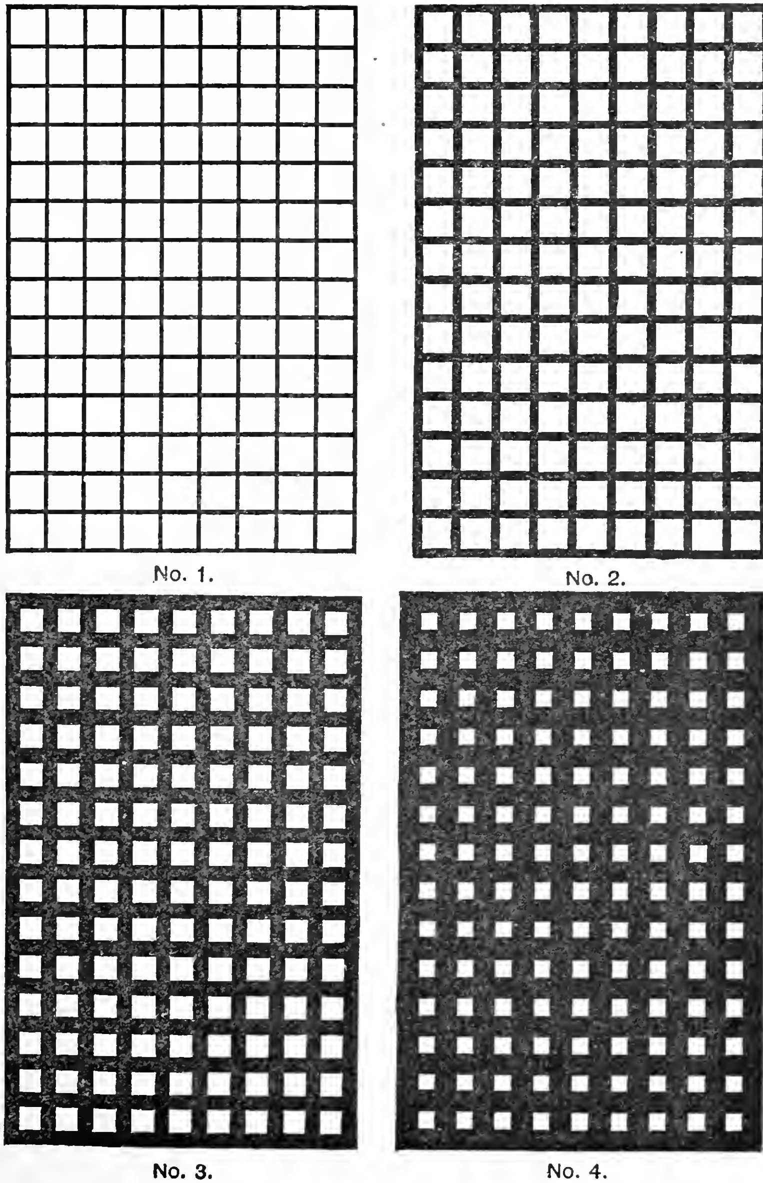


FIG. 7 THE RINGELMAN SCALE FOR GRADING THE DENSITY OF SMOKE

total absorption of the various gases, care must be taken that the absorbing solutions are in good condition, and they should therefore be renewed from time to time. If the flue gas is to be collected over water, a saturated salt solution should be used, as water has a tendency to retain some of the CO_2 when a considerable quantity is present, and to give it up later when there is a smaller quantity of this gas, thus causing errors in the results. Fig. 6 shows the type of Orsat apparatus generally used.

If determinations of the relative density of the smoke are to be made during the trial, the Ringelman smoke charts shown in Fig. 7 may conveniently be used. These are placed in a horizontal row about fifty feet from the observer, and as nearly as convenient in line with the chimney. At this distance the lines become invisible and the cards appear as different shades of gray. The observer by glancing from the chimney to the cards determines which card most nearly corresponds to the color of the smoke and makes a record accordingly.

Location of Appliances

Of prime importance in taking observations is the location of the apparatus used. On account of the variation in different types of boiler settings it will always be necessary to describe clearly in the report of the test the location of all apparatus. This is best done by indicating on drawings or diagrams their position on the setting.

Feed Water Temperature.—As the methods used in supplying feed water to a boiler vary, so does also the location of the thermometer for the temperature measurement of such feed water. If an injector be used, it should receive steam directly through a covered pipe from the boiler being tested, and the temperature of the feed water should in this case be taken from the supply tank furnishing the water to the injector. It is here assumed that the heat of the steam operating the injector is returned to the boiler from which it was taken, so that the supply pipe between the boiler and injector, if long, should be covered to prevent radiation. If a pump be used for feeding the boiler, the temperature of the feed water should be taken by a thermometer in the discharge pipe as near the boiler as possible. If this is done, the water may or may not be pumped through a feed water heater after leaving the pump.

It is always essential that the heat carried into the boiler by the feed water should be known, and it is well to record its temperature before and after it passes through any kind of heater or economizer in order that the effect of such device may be given proper credit.

The location of thermometers for the determination of boiler room and external air temperatures should be such that drafts or heat rays will be avoided. The flue gas temperature should be taken at a point where the gases leave the boiler and pass into the breeching on their way to the stack. As the temperature in a transverse section of the flue will vary, several readings should be taken at different points of the same section. Observations of the draft are usually made at several points of the setting. The one between the damper and the boiler is, however, the more important, and should be taken at a point close to the flue gas thermometer or possibly in the same transverse section. The force of draft in furnace and ash-pit may be taken through the firing and ash-pit doors, but is preferably taken through holes left in the side walls. The calorimeter and the thermometer cup for determining superheat should be attached to the vertical steam pipe as it leaves the boiler. The sampling tube for the flue gas was explained in the last section. It should be inserted in the flue at the point where the flue gas temperature and draft are obtained.

III REPORT OF THE TRIAL

Forms.—The data and results of a boiler trial should be reported in the manner given in Form VI, which is the complete form advised by the Boiler Test Committee of the American Society of Mechanical Engineers, Code of 1899. The items printed in italics correspond to the items in the "Short Form" of report recommended for commercial tests. For more elaborate trials the code recommends that the full log of the trial be shown graphically by means of a chart, Fig. 8.

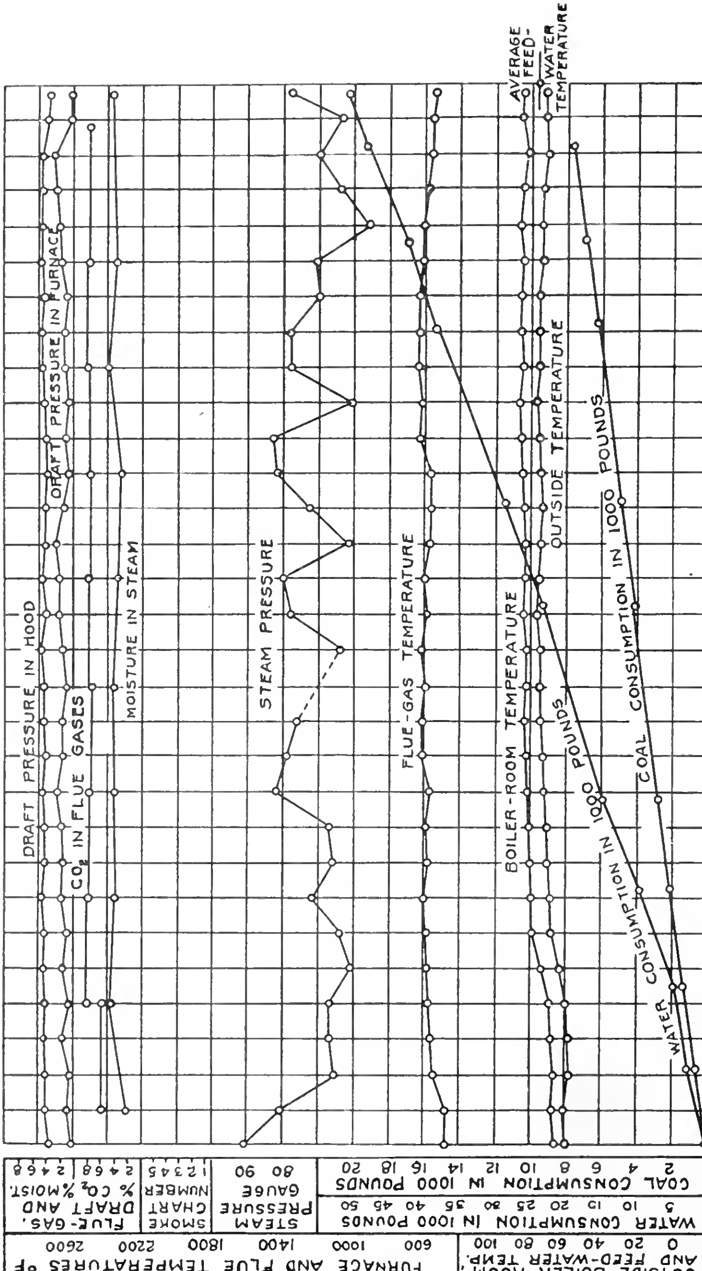


FIG. 8 CHART SHOWING LOG OF BOILER TESTS

FORM VI

DATA AND RESULTS OF EVAPORATIVE TESTS

Arranged in accordance with the Complete Form advised by the Boiler Test Committee of the American Society of Mechanical Engineers. Code of 1899.

Made by............................of......................boiler at ....to determine..

Principal conditions governing the trial..

*Kind of fuel**..
Kind of furnace..
State of the weather...
Method of starting and stopping the test ("standard" or "alternate")
1. *Date of trial*..
2. *Duration of trial*.. hours

Dimensions and Proportions

(A complete description of the boiler and drawings of the same if of unusual type, should be given on an annexed sheet)

3. *Grate surface*............*width*............*length*............*area*............ sq. ft.
4. Height of furnace.. in.
5. Approximate width of air spaces in grate.................................. in.
6. Proportion of air space to whole grate surface.......................... per cent
7. *Water-heating surface*... sq. ft.
8. *Superheating surface*.. sq. ft.
9. Ratio of water-heating surface to grate surface.......................... —to 1
10. Ratio of minimum draft area to grate surface............................ 1 to—

Average Pressures

11. *Steam pressure by gage*..lbs. per sq. in.
12. *Force of draft between damper and boiler*.................................in. of water
13. Force of draft in furnace..in. of water
14. Force of draft or blast in ash pit..in. of water

Average Temperatures

15. Of external air.. deg.
16. Of fireroom.. deg.
17. Of steam... deg.
18. Of feed water entering heater... deg.
19. Of feed water entering economizer... deg.
20. *Of feed water entering boiler*... deg.
21. *Of escaping gases from boiler*.. deg.
22. Of escaping gases from economizer... deg.

Fuel

23. Size and condition.. ....
24. Weight of wood used in lighting fire....................................... lbs.
25. *Weight of coal as fired*... lbs.
26. *Percentage of moisture in coal*... per cent
27. *Total weight of dry coal consumed*... lbs.
28. *Total ash and refuse*.. lbs.
29. Quality of ash and refuse... ....
30. Total combustible consumed.. lbs.
31. *Percentage of ash and refuse in dry coal*.................................. per cent

Proximate Analysis of Coal

		Of Coal.	Of Combustible.
32.	Fixed carbon..............	per cent	per cent
33.	Volatile matter...........	per cent	per cent
34.	Moisture..................	per cent	——
35.	Ash.......................	per cent	——
		100 per cent	100 per cent
36.	Sulphur, separately determined..........	per cent	per cent

*The items printed in italics correspond to the items in the "Short Form of Code."

Ultimate Analysis of Dry Coal

		Of Coal.	Of Combustible.
37.	Carbon (C)	per cent	per cent
38.	Hydrogen (H)	per cent	per cent
39.	Oxygen (O)	per cent	per cent
40.	Nitrogen (N)	per cent	per cent
41.	Sulphur (S)	per cent	per cent
42.	Ash	per cent	—
		100 per cent	100 per cent
43.	Moisture in sample of coal as received	per cent	per cent

Analysis of Ash and Refuse

44.	Carbon	per cent
45.	Earthy matter	per cent

Fuel per Hour

46.	*Dry coal consumed per hour*	lbs.
47.	Combustible consumed per hour	lbs.
48.	*Dry coal per square foot of grate surface per hour*	lbs.
49.	Combustible per square foot of water-heating surface per hour	lbs.

Calorific Value of Fuel

50.	*Calorific value by oxygen calorimeter, per lb. of dry coal*	B. T. U
51.	*Calorific value by oxygen calorimeter, per lb. of combustible*	B. T. U
52.	Calorific value by analysis, per lb. of dry coal	B. T. U
53.	Calorific value by analysis, per lb. of combustible	B. T. U

Quality of Steam

54.	*Percentage of moisture in steam*	per cent
55.	*Number of degrees of superheating*	deg.
56.	Quality of steam (dry steam =unity). (For exact determination of the factor of correction for quality of steam see section on computation of results.)	

Water

57.	*Total weight of water fed to boiler*	lbs.
58.	Equivalent water fed to boiler from and at 212 degrees	lbs.
59.	*Water actually evaporated, corrected for quality of steam*	lbs.
60.	Factor of evaporation	lbs.
61.	Equivalent water evaporated into dry steam from and at 212 degrees. (Item 59 × Item 60.)	lbs.

Water per Hour

62.	*Water evaporated per hour, corrected for quality of steam*	lbs.
63.	*Equivalent evaporation per hour from and at 212 degrees*	lbs.
64.	*Equivalent evaporation per hour from and at 212 degrees per square foot of water-heating surface*	lbs.

Horse-Power

65.	*Horse-power developed. (34½ lbs of water evaporated per hour into dry steam from and at 212 degrees, equals one horse-power.)*	H. P.
66.	*Builders' rated horse-power*	H. P.
67.	*Percentage of builders' rated horse-power developed*	per cent

Economic Results

68.	*Water apparently evaporated under actual conditions per pound of coal as fired. (Item 57 ÷ Item 25.)*	lbs.
69.	*Equivalent evaporation from and at 212 degrees per pound of coal as fired. (Item 61 ÷ Item 25.)*	lbs.
70.	*Equivalent evaporation from and at 212 degrees per pound of dry coal. (Item 61 ÷ Item 27.)*	lbs.
71.	*Equivalent evaporation from and at 212 degrees per pound of combustible. (Item 61 ÷ Item 30.)*	lbs.

(If the equivalent evaporation, Items 69, 70 and 71, is not corrected for the quality of steam, the fact should be stated.)

Efficiency

72.	*Efficiency of the boiler; heat absorbed by the boiler per pound of combustible divided by the heat value of one pound of combustible*	per cent
73.	*Efficiency of boiler, including the grate; heat absorbed by the boiler, per pound of dry coal, divided by the heat value of one pound of dry coal*	per cent

Cost of Evaporation

74.	*Cost of coal per ton——lbs. delivered in boiler room*	$.........
75.	Cost of fuel for evaporating 1,000 lbs of water under observed conditions	$.........
76.	*Cost of fuel used for evaporating* 1,000 *lbs. of water from and at* 212 *degrees.*	$.........

Smoke Observations

77.	Percentage of smoke as observed	per cent
78.	Weight of soot per hour obtained from smoke meter	ounces
79.	Volume of soot per hour obtained from smoke meter	cu. in.

Methods of Firing

80. Kind of firing (spreading, alternate, or coking)....................
81. Average thickness of fire....................
82. Average intervals between firings for each furnace during time when fires are in normal condition....................
83. Average interval between times of levelling or breaking up....................

Analyses of the Dry Gases

84.	Carbon dioxide (CO_2)	per cent
85.	Oxygen (O)	"
86.	Carbon monoxide (CO)	"
87.	Hydrogen and hydrocarbons	"
88.	Nitrogen (by difference) (N)	
		100 per cent

HEAT BALANCE, OR DISTRIBUTION OF THE HEATING VALUE OF THE COMBUSTIBLE
TOTAL HEAT VALUE of 1 lb. of Combustible....................B. T. U.

	B. T. U.	Per Cent
1. Heat absorbed by the boiler = evaporation from and at 212 degrees per pound of combustible × 965.7.		
2. Loss due to moisture in coal = per cent of moisture referred to combustible ÷ 100 × [(212 − t) + 966 + 0.48 (T − 212)] (t = temperature of air in the boiler room, T = that of the flue gases)		
3. Loss due to moisture formed by the burning of hydrogen = per cent of hydrogen to combustible ÷ 100 × 9 × [(212 − t) + 966 + 0.48(T − 212)]		
4.* Loss due to heat carried away in dry chimney gases = weight of gas per pound of combustible × 0.24 × (T − t).		
5.† Loss due to incomplete combustion of carbon = $\frac{CO}{CO_2 + CO} \times \frac{\text{per cent C in combustible}}{100} \times 10{,}150$.		
6. Loss due to unconsumed hydrogen and hydrocarbons, to heating the moisture in the air, to radiation, and unaccounted for. (Some of these losses may be separately itemized if data are obtained from which they may be calculated.)		
Totals		100.00

*The weight of gas per pound of carbon burned may be calculated from the gas analyses as follows:

$$\text{Dry gas per pound carbon} = \frac{11\,CO_2 + 8O + 7\,CO + (N)}{3\,(CO_2 + CO)},$$

in which CO_2, CO, O, and N are the percentages by volume of the several gases. As the sampling and analyses of the gases in the present state of the art are liable to considerable errors, the result of this calculation is usually only an approximate one. The heat balance itself is also only approximate for this reason as well as for the fact that it is not possible to determine accurately the percentage of unburned hydrogen or hydrocarbons in the flue gases.

The weight of dry gas per pound of combustible is found by multiplying the dry gas per pound of carbon by the percentage of carbon in the combustible, and dividing by 100.

†CO_2 and CO are respectively the percentage by volume of carbonic acid and carbonic oxide in the flue gases. The quantity 10,150 = Number of heat units generated by burning to carbonic acid one pound of carbon contained in carbonic oxide.

Starting and Stopping the Test

Standard Method.—Steam being raised to the working pressure, remove rapidly all fire from the grate, close the damper, clean the ash-pit, and as quickly as possible start a new fire with weighed wood and coal, noting the time and the water level while the water is in a quiescent state, just before lighting the fire. At the end of the test, remove the whole fire, which has been burned low, clean the grates and ash-pit, and note the water level when the water level is in a quiescent state, and record the time of hauling the fire. The water level should be as nearly as possible the same as at the beginning of the test. If it is not the same a correction should be made by computation, and not by operating the pump after the test is complete.

Alternate Method.—The boiler being thoroughly heated by a preliminary run, the fires are to be burned low and well cleaned. Note the amount of coal left on the grate as nearly as it can be estimated; note the pressure of steam and the water level. Note the time and record it as the starting time. Fresh coal, which has been weighed, should now be fired. The ash-pits should be thoroughly cleaned at once after starting. Before the end of the test the fires should be burned low, just as before the start, and the fires cleaned in such a manner as to leave a bed of coal on the grates of the same depth and in the same condition as at the start. When this stage is reached, note the time and record it as the stopping time. The water level and steam pressure should previously be brought as nearly as possible to the same point as at the start. If the water level is not the same as at the start, a correction should be made by computation, and not by operating the pump after the test is completed.

The two methods given above for starting and stopping the test are taken from the A. S. M. E. Code for conducting steam boiler trials. When the alternate method is used, several precautions regarding the observations are necessary. The time of starting and stopping should be noted when the smallest amount of fuel is on the grate, and when it is in the most burned-out condition, i. e., just before firing fresh coal after cleaning, and when the water level is in its most quiet condition and the least raised by ebullition. This condition of fire and of water level can be duplicated immediately after cleaning the fire, but there is no certainty of duplication of any condition when there is a bright fire

and consequent rapid steaming. If the water level is noted at the starting of the test when it is raised by a bright fire, and at the end of a test when it is depressed by the stoppage of violent ebullition or of rapid circulation due to the cooling of the fire, the boiler will be credited with more water than was really evaporated. As such a fall in water level is easily produced by opening fire doors and checking draft, it should be guarded against especially when using bituminous or flaming coals. The greatest care should also be taken that the bed of coal at the end does not contain more waste material, which belongs to the ash, than it did at the beginning.

Computation of Results

On account of the variations in the types of boilers and furnaces, no specific directions can be given for the measurement of grate surface, height of furnace and other furnace proportions. The heating surface should be computed from the surface of shells, tubes and fire-boxes in contact with fire or hot gases. The outside diameter of water tubes and the inside diameter of fire tubes should be used in this computation. All surfaces below the mean water level which have water on one side and products of combustion on the other are to be considered as water-heating surface, and all surfaces above the mean water level which have steam on one side and products of combustion on the other are to be considered as superheating surface.

The following directions show how some of the results to be derived from a boiler trial may be obtained. The calculation of other items is self-evident.

Item 26, the moisture in the coal, should be obtained by the chemist by drying the sample collected during the test, for one hour in a sand or air bath at a temperature between 240° and 280° F. Sometimes the moisture is obtained by drying a known quantity of the coal above the boiler; however, if this method is used, it should be so stated in the report. The first method is always to be preferred. (See Section VI, page 48).

Item 27=Item 25×(100−Item 26)

Item 30=Item 27×(100−Item 42)−(Item 28×Item 44)

As this is dependent upon the ultimate analysis of the coal, which is not always available, the following may be used:

Item 30=Item 27−Item 28

The latter, however, is in error, due to the unaccounted-for ash passing over the bridge wall.

Item 51=Item 50÷(100—Item 42)

or =Item 50÷[Item 27—(Item 28×Item 45)]

in which the former depends again upon the ultimate analysis of the coal.

$$\text{Items 52 and 53} = 14{,}600\ C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000\ S,$$

in which C, H, O and S refer to the proportions of carbon, hydrogen, oxygen and sulphur respectively, as determined by the ultimate analysis.

$$\text{Item 54} = 100 \times \frac{H - 1146.6 - 0.48\ (T - 212)}{L}$$

$$\text{or} \quad = 100 \times \frac{\text{lbs. of moisture separated}}{\text{lbs. of steam} + \text{lbs. of moisture separated}}$$

in which H=total heat and L=latent heat per pound of steam at the pressure in the steam pipe, and T=temperature of the throttled and superheated steam in the calorimeter. The first formula applies to throttling and the second to separating calorimeters.

Item 55 should be taken as the difference between the reading of the thermometer for superheated steam and the readings of the same thermometer for saturated steam at the same pressure as determined by a special experiment and not by reference to the steam tables.

Item 56=100—Item 54

For the exact determination of the factor of correction for quality of steam we have the following:

For wet steam, $F = Q + P\left(\frac{T_1 - J_1}{H - J_1}\right)$, and

For superheated steam, $F = 1 + \frac{0.48K}{H - J_1}$, in which

F = factor of correction

Q = quality of steam

P = per cent of moisture in steam

K = degrees of superheating in steam

H = total heat of the steam due to the steam pressure

T_1 = total heat in the water at the temperature due to the steam pressure

J_1 = total heat in the feed water due to the temperature

Item 59 = Item 57 × Item 56

Item 60 $=\frac{H-h}{965.7}$, in which H and h are respectively the total heat in the steam of the average observed pressure and in water of the average observed temperature of the feed. This item may usually be obtained directly from steam tables giving the factors for different pressures and feed water temperatures.

Item 61 = Item 59 × Item 60
Item 62 = Item 59 ÷ Item 2
Item 63 = Item 61 ÷ Item 2
Item 64 = Item 63 ÷ Item 7
Item 65 = Item 63 ÷ 34.5

This is held to be equivalent to 30 pounds of water evaporated from 100° F. into dry steam at 70 pounds gage pressure. The former equals 33,317 B. T. U. per hour and the latter 33,305 B. T. U. per hour.

Item 66.—This item should give besides the rated horsepower the basis (square feet of heating surface) upon which this rating is made.

Item 67 = Item 65 ÷ Item 66

The necessary computations for economic results and efficiency, items 68 to 73, are indicated in the form of report.

IV Report of Boiler Tests with Illinois Coals

The following tables contain a summary of the results of boiler tests made by the department of Mechanical Engineering at the University of Illinois. For the most part these tests have been made, as stated in the introduction, for purposes of instruction in the method of boiler testing, although a considerable number were made for investigational purposes or as thesis work. As a rule, they have been conducted under the direct supervision of a member of the instructional staff of the department, but at times when experiments were being made with special appliances, the representative of the company interested was present to take charge of the test.

Coals Tested

The coals used in these tests were mostly those purchased under the yearly contracts of the University. In a few cases, special coals were purchased, while other tests were made on

coals sent to the University by various coal companies and manufacturing concerns to determine the evaporative efficiency or their behavior on various kinds of stokers.

35 coals were tested, representing 14 counties of Illinois. These are given in the list below together with the commercial size of the coal.

	County	*Town*	*Commercial Size*
1	Christian	Pana	Lump
2	Christian	Pana	Slack
3	Christian	Pana	Sreeenings
4	Coles	Paradise	Lump
5	Gallatin	Junction	Pea
6	Macon	Niantic	Nut
7	Macoupin	Mt. Olive	Lump
8	Madison	Glen Carbon	Lump
9	Marion	Odin	Lump
10	Marion	Odin	Pea
11	Marion	Odin	Slack
12	McLean	Bloomington	Lump
13	McLean	Colfax	Lump
14	Menard	Athens	Lump
15	Perry	Du Quoin	Lump
16	Perry	Du Quoin	Pea
17	Perry	Du Quoin	Slack
18	Sangamon	Barclay	Pea
19	Sangamon	Dawson	Pea
20	Sangamon	Divernon	Lump
21	Sangamon	Lowder	Slack
22	Sangamon	Ridgely	Pea
23	Sangamon	Riverton	Pea
24	Sangamon	Sringfield	Pea
25	Sangamon		Lump
26	Shelby	Moweaqua	Lump
27	Vermilion	Catlin	Screenings
28	Vermilion	Fairmount	Screenings
29	Vermilion	Muncie	Slack
30	Vermilion	Oakwood	Lump
31	Vermilion	Oakwood	Pea
32	Vermilion	Oakwood	Screenings
33	Williamson	Carterville	Washed Pea
34	Williamson	Herrin	New Kentucky Pea
35	Williamson	Herrin	New Kentucky Screenings

Boilers Tested

The tests were made at the power plants of the University and the neighboring towns, under water-tube and fire-tube boilers of the following types:

Stirling water-tube boiler.............. 2 settings
National water-tube boiler.............. 2 settings
Heine water-tube boiler. .... 1 setting
Babcock & Wilcox water-tube boiler..... 8 settings
Horizontal tubular boiler ....11 settings

The settings of these boilers include the following:

1 Murphy smokeless furnace
2 Roney automatic stokers
2 Green chain grate stokers

1 Babcock & Wilcox chain grate
1 Brightman stoker

The remainder of the furnaces were hand-fired with plain or rocking grates.

Results of Tests

The results of these tests are shown in Tables III and IV, arranged according to the counties in which the coal was mined. Table III gives the conditions of temperature, pressure, heating surface and grate area under which the tests were made, and Table IV gives a few of the most important results. In some cases the heat value of the coals used was not obtained and several of the columns dependent upon it are left vacant. The headings of the tables are self-explanatory. Where a series of tests was made with the same coals under like conditions, the average of the series is reported together with the number of tests in the series. Where the coal and steam have been assumed moisture free and when the moisture in the coal was obtained by drying a known amount above the boiler, indications have been made in the tables.

In the computation of results, the usual correction for quality of steam by proportional weights of steam and water was used. The combustible was computed from the weights of coal and ash and not from the ultimate analysis of the coal, and it is, therefore, in slight error to the extent of the ash which passed over the bridge wall. The basis for the rating of the boilers varied from 10 to 15 square feet of heating surface per horse-power according to the different types of boilers used. The B. T. U. of the coal, given in the table, were obtained from an analysis of the sample taken during the test.

Discussion of Results

On account of the wide variation of conditions obtaining in the tests reported, an exact comparison was hardly possible. A general comparison of results with different types of boilers and grates has, however, been attempted. Such a comparison is shown in Table V, which contains the general average of the results of all trials made with the same type of boiler and grate, irrespective of all other conditions. It also shows the average of

TABLE III BOILER TESTS WITH ILLINOIS COALS MADE BY THE MECHANICAL ENGINEERING DEPARTMENT, UNIVERSITY OF ILLINOIS, 1894-1905. GENERAL DESCRIPTION AND PROPORTIONS

Number	Description of Coals: County	Description of Coals: Town	Description of Coals: Commercial Size	Type of Boiler and Grate	Location of Boiler	Date of Trial	Duration of Trial	Grate Surface	Water Heating Surface	Steam Pressure, Gage	Force of Draft between Damper and Boiler	Temperature of Feed Water	Temperature of Escaping Flue Gases
							Hours	Sq. ft.	Sq. ft.	Lbs. Sq. in.	Inches, Water	°Fahr.	°Fahr.
				A. S. M. E. Code No.		1	2	3	7	11	12	20	21
1	Christian	Pana	Slack	B. & W. No. 1 & 2, plain grate	Urbana & Cham. Elec. Light Pl'nt.	June 1891	10.12	52.1	2340	90.2	.220	59.1	498
2	do	do	Pea	do	do	June 1891	10.00	51.0	2264	91.3	.220	60.9	484
3	do	do	Screenings	do	do	June 1891	10.00	51.0	2264	95.9	.200	60.0	464
4	do	do	Lump and slack	do	do	June 1891	10.18	51.0	2264	95.0	.325	60.7	529
5	Coles	Paradise	Lump	Hor. Tub. No. 2, plain grate	Univ. of Illinois, M. E. Lab.	Feb. 1897	8.00	18.7	533	82.1	.405	17.5	519
6	Gallatin	Junction	Pea	National W. T. No. 4 Murphy furnace	Univ. of Illinois, Cent. Heat. Pl'nt.	Mar. 1899	7.25	60.7	2579	108.1	.580	49.1	481
7	Macon	Niantic	Nut	B. & W. No. 5, plain grate	do	Jan. 1895	10.00	51.0	2450	59.5	.300	49.6	485
8	Macoupin	Mt Olive	Lump	Hor. Tub. No. 2, plain grate	Univ. of Illinois, M. E. Lab.	Feb. 1897	8.00	18.7	533	75.8	.470	47.0	567
9	Madison	Glen Carbon	Lump	B. & W. No. 2, chain grate	Univ. of Illinois, Cent. Heat. Pl'nt.	May 1901	8.00	28.0	1486	108.1	.600	60.0	571
10	Marion	Odin	Lump	Hor. Tub. No. 1, plain grate	Univ. of Illinois, M. E. Lab.	Apr. 1891	7.74	18.7	533	70.3	.262	56.3	489
11	do	do	Lump	Hor. Tub. No. 2, plain grate	do	Apr. 1895	10.10	18.7	533	59.0	.200	53.7	680
12	do	do	Pea	do	do	June 1896	9.50	18.7	533	67.8	.163	61.1	508
13	do	do	Pea	Hor. Tub. No. 1, plain grate	do	Oct. 1896	8.00	16.6	517	73.0	.200	59.6	494

14	.... do	.... do	Pea	Hor. Tub. No. 3, 4, plain grate	Urbana & Cham., Water Works	Jan. 1897	8.00	45.0	2260	70.8	.394	128.0	359
15	.... do	.... do	Lump	Hor. Tub. No. 4, rocking grate	Univ. of Illinois Cent. Heat. Pl'nt.	Mar. 1895	9.38	30.0	1010	69.4	.219	52.2	560
16	.... do	.... do	Lump	B. & W. No. 5, plain grate	.... do	Jan. 1895	8.71	51.0	2150	67.8	.330	50.9	478
17	.... do	.... do	Pea	.... do	.... do	Mar. 1899	8.00	51.0	2150	103.7	.600	49.7	518
18	.... do	.... do	Lump	Stirling No. 3, plain grate	.... do	Nov. 1896	7.85	13.5	525	82.0	.250	21.8	544
19	.... do	.... do	Lump	B. & W. No. 2 plain grate	Urbana & Cham. Elec. L. & P. Co.	June 1891	10.00	51.0	2261	98.5	.210	59.5	482
20	.... do	.... do	Slack	.... do	.... do	Dec. 1896	8.00	51.0	2261	106.4	.730	15.0	462
21	.... do	.... do	Duff	Stirling No. 7 & 8, plain grate	.... do	Mar. 1905	23.60	50.9	2587	110.6	.650	178.5	591
22	.... do	.... do	Pea	Nat. W. T. No. 4, Murphy furnace	.... do	Jan. 1899	8.00	60.7	2579	81.7	.515	53.0	502
23	McLean	Bloomington	Lump	Hor. Tub. No. 2, plain grate	Univ. of Illinois, Cent. Heat. Pl'nt	Feb. 1895	10.76	18.7	533	65.6	.213	52.2	578
24	.... do	.... do	Lump	B. & W. No. 5, plain grate	Univ. of Illinois, M. E. Lab.	Dec. 1894	6.00	51.0	2450	[illegible]3.6	.300	53.6	......
25	.... do	Colfax	Lump	B. & W. No. 1, plain grate	Univ. of Illinois, Cent. Heat. Pl'nt	May 1902	8.00	35.0	1186	106.3	.500	70.5	.....
26	Menard	Athens	Lump	Hor. Tub. No. 2, plain grate	.... do	Mar. 1897	7.83	18.7	533	77.5	.190	50.6	523
27	Perry	Du Quoin	Lump	Hor. Tub. No. 1, plain grate	Univ. of Illinois, M. E. Lab.	Oct. 1895	8.00	16.6	547	63.1	.236	63.6	528
28	.... do	.... do	Lump	Hor. Tub. No. 2, plain grate	.... do	June 1896	9.25	18.7	533	69.0	.180	61.6	503
29	.... do	.... do	Slack	Hor. Tub., plain grate	.... do	Apr. 1898	8.00	22.5	870	93.0	.320	177.7	535
30	.... do	.... do	Lump	Hor. Tub. No. 1, rocking grate	Twin City Ice & Cold Storage Co.	Feb. 1895	9.00	30.0	1010	65.6	.257	48.4	519
31	.... do	.... do	Lump	B. & W. No. 5, plain grate	Univ. of Illinois, Cent. Heat. Pl'nt	Feb. 1895	9.50	51.0	2450	68.3	.303	49.8	515
32	.... do	.... do	Pea	B. & W. No. 2, plain grate	.... do	Mar. 1901	12.00	51.0	2261	108.5	.700	69.2	120
33	Sangamon	Barclay	Pea	Hor. Tub rocking grate	Urbana & Cham Elec. L. & P. Co.	Apr. 1898	7.50	25.0	......	88.8	.300	100.1	403
34	.... do	Dawson	Pea	B. & W. No. 5 & 6, plain grate	Decatur, Illinois, Water Works	Mar. 1899	8.00	51.0	2450	105.8	.600	53.4	539
35	.... do	.... do	Pea	Nat. W. T. No. 4, Murphy furnace	Univ. of Illinois, Cent. Heat. Pl'nt	Mar. 1899	8.00	60.7	2579	101.3	.540	52.1	503
36	.... do	Divernon	Lump	B. & W. No. 2, chain grate	.... do	May 1901	8.00	28.0	1486	102.3	.600	60.6	512
37	.... do	Lowder	Slack	.... do	.... do	Apr. 1901	8.00	28.0	1486	119.0	.325	78.5	453
38	.... do	Ridgely	Pea	Nat. W. T. No. 4, Murphy furnace	.... do	Feb. 1899	8.00	60.7	2579	106.5	.550	49.5	495

TABLE III (*Concluded*)

Number	Description of Coals: County	Description of Coals: Town	Description of Coals: Commercial Size	Type of Boiler and Grate	Location of Boiler	Date of Trial	Duration of Trial	Grate Surface	Water Heating Surface	Steam Pressure Gage	Force of Draft between Damper and Boiler	Temperature of Feed Water	Temperature of Escaping Flue Gases
							Hours	Sq. ft.	Sq. ft.	Lbs. Sq. in.	Inches, Water	°Fahr.	°Fahr.
				A. S. M. E. Code No.		1	2	3	7	11	12	20	21
39	Sangamon	Riverton	Pea	Nat. W. T. No. 4, Murphy furnace	Univ. of Illinois, Cent. Heat Pl'nt	Mar. 1899	8.00	60.7	2579	110.8	.420	48.3	462
40	do	do	Pea	B. & W. No. 5 & 6, Roney stoker	do	Jan. 1904	24.00	51.0	2353	119.4	.270	60.6	559
41	do	do	Pea	B. & W. No. 2, chain grate	do	Dec. 1903	8.00	28.0	1486	113.7	.700	63.7	530
42	do	do	Pea	do	do	Jan. 1904	8.00	28.0	1486	113.7	.670	63.2	535
43	do	do	Pea	do	do	Feb. 1904	8.00	28.0	1486	115.0	.630	72.0	435
44	do	do	Pea	do	do	Mar. 1904	8.00	28.0	1486	118.7	.580	73.5	141
45	do	do	Pea	do	do	Jan. 1904	8.00	28.0	1186	114.4	.170	65.2	464
46	do		Lump	Hor. Tub. No. 2, plain grate	Univ. of Illinois, M. E. Lab.	Feb. 1897	8.51	18.7	533	75.2	.306	48.0	519
47	do			B. & W. No. 2, chain grate	Univ. of Illinois, Cent. Heat. Pl'nt	Apr. 1904	8.00	28.0	1486	121.6	.145	72.3	492
48	do			Nat. W. T. No 1, chain grate	do	Jan. 1905	9.77	59.0	2513	117.8	.360	79.8	635
49	do			do	do	Apr. 1905	10.02	55.8	2513	122.9	.370	73.6	584
50	do	Springfield	Pea	B. & W. No. 2, plain grate	do	Apr. 1901	8.19	35.0	1486	104.9	.620	63.5	462
51	do	do	Pea	B. & W. No. 2, chain grate	do	Apr. 1901	8.00	35.0	1486	102.8	.610	57.4	519
52	do	do	Pea	B. & W. No. 6, Roney stoker	do	Nov. 1905	10.00	51.0	2353	128.4	.290	61.5	608
53	Shelby	Moweaqua	Lump	B. & W. No. 5, plain grate	do	Jan. 1895	10.00	51.0	2150	55.0	.300	51.5	489
54	Vermilion	Catlin	Screenings	Murray hor. tub. No. 1, 2, 3, rocking grate	Urbana Light, Heat & Power Co.	Mar. 1905	47.66	33.0	1456	98.9	.610	130.6	393

55	.... do	Fairmount......	Screenings..	B. & W. No. 2, plain grate........	Urbana & Cham. Elec. L. & P. Co.	Dec. 1896	8.00	51.0	2264	108.2	.740	54.0	487
56	.... do	Muncie..........	Slack........	Hor. Tub. No. 2 & 3 plain grate........	Urbana & Cham. Water Works.....	Nov. 1895	10.00	22.5	1060	71.8	.430	110.0	301
57	.... do	Oakwood........	Lump	Stirling No. 7 & 8, plain grate	Urbana & Cham. Elec. L. & P. Co.	Mar. 1905	21.00	50.9	2587	112.3	.790	182.8	631
58	.... do	... do	Screenings..	.... do	.... do	Apr. 1905	10.80	50.9	2587	110.7	.790	200.0	616
59	.... do	.... do	Screenings..	B. & W. plain grate........	.... do	Apr. 1905	10.33	61.0	2860	102.0	.330	178.0	565
60	.... do	.... do	Screenings..	Heine chain grate........	.... do	May 1905	8.03	72.0	3160	111.9	.710	63.5	592
61	.... do	.... do	Pea	B. & W. No. 6, Roney stoker.....	Univ. of Illinois, Cent. Heat. Pl'nt.	Nov. 1905	10.00	51.0	2353	133.2	.226	98.3	593
62	Williamson ...	Carterville	W. Pea& duff	.... do	.... do	Nov. 1905	10.00	51.0	2353	132.9	.236	61.0	609
63	.... do	Herrin	New Ky. Pea	B. & W. No. 2, chain grate.......	.... do	Apr. 1901	9.33	28.0	1186	117.0	.190	65.0	529
64	.... do	... do	do W. Scre'n	.... do	.... do	Apr. 1901	20.00	28.0	1486	120.1	.510	62.0	531
65	.... do	.... do	do W. Scre'n	B. & W. No. 5 & 6, Roney stoker......	.... do	Feb. 1901	12.00	51.0	2353	117.9	.166	57.8	657

TABLE IV BOILER TESTS WITH ILLINOIS COALS MADE BY THE MECHANICAL ENGINEERING DEPARTMENT

UNIVERSITY OF ILLINOIS 1894-1905

AVERAGED RESULTS

Number	Description of Coals: County	Town	Commercial Size	Type of Boiler and Grate	Number of Tests Averaged	Dry Coal per sq. ft. of Grate Surface per hr.	Horsepower Developed by Boiler	Percentage of Rated Horsepower Developed	Equiv. Evaporation from and at 212° Fahr.: Per sq. ft. of Waterheating Surface per hr.	Per pound of Dry Coal	Per pound of Combustible	B. T. U. per pound of Dry Coal	Efficiency of Boiler including Grate
					See Note	lbs.		%	lbs.	lbs.	lbs.		%
				A. S. M. E. Code No.		49	65	67	64	70	71	50	73
1	Christian	Pana	Slack	B. & W. No. 1 & 2. plain grate	4†	15.10	108.5	51.7	1.60	4.90	6.38	....	......
2	.... do	.... do	Pea	.... do	1†	13.80	110.8	52.8	1.69	5.41	6.63	....	......
3	.... do	.... do	Screenings	.... do	1†	14.90	114.9	54.7	1.75	5.21	6.18	....	......
4	.... do	.... do	Lump and Slack	.... do	1†	20.40	196.4	93.5	2.99	6.50	7.44	....	......
5	Coles	Paradise	Lump	Hor. Tub. No. 2. plain grate	2	13.56	52.0	130.0	3.37	7.05	7.78	11430	59.6
6	Gallatin	Junction	Pea	National W. T. No. 4 Murphy furnace	4†	18.43	206.3	82.5	2.76	6.36	7.09	....	......
7	Macon	Niantic	Nut	B. & W. No. 5. plain grate	1*	18.74	135.4	61.5	1.19	4.89	5.95	....	......
8	Macoupin	Mt. Olive	Lump	Hor. Tub. No. 2. plain grate	2	13.79	52.1	130.2	3.38	6.96	7.53	....	......
9	Madison	Glen Carbon	Lump	B. & W. No. 2, chain grate	3	32.40	135.1	90.1	3.14	5.15	7.17	....	......
10	Marion	Odin	Lump	Hor. Tub. No. 1, plain grate	5	10.38	36.6	91.5	2.37	6.18	7.73	....	......
11	.... do	... do	Lump	Hor. Tub. No. 2. plain grate	5*	13.63	45.9	114.7	2.97	6.19	7.14	....	......
12	.... do	... do	Pea	.... do	3*	8.41	24.6	61.5	1.59	5.38	6.25	....	......
13	.... do	.... do	Pea.	Hor. Tub. No. 1, plain grate	1	11.99	35.5	88.7	2.21	6.13	7.32	11070	53.5

14	.... do	.... do	Pea...............	Hor. Tub. No. 3 & 4 plain grate.........	3	10.31	84.6	47.0	1.29	6.29	7.49	......	....
15	.... do	.... do	Lump.............	Hor. Tub. No. 4 rocking grate.....	2*	22.49	135.0	135.0	4.61	6.91	7.87	......	....
16	.... do	.... do	Lump.............	B & W No. 5 plain grate...............	5	20.20	176.4	80.2	2.48	5.91	7.00	......	....
17	.... do	.... do	Pea...............	.... do...............	1	27.10	555.7	126.3	3.91	6.92	8.82	......	....
18	.... do	.... do	Lump.............	Stirling No. 3 plain grate...............	7	19.91	51.2	85.3	3.37	6.57	7.63	11633	51.5
19	.... do	.... do	Lump.............	B & W No. 2 plain grate...............	1†	15.20	129.1	61.5	1.97	5.74	6.51	......	....
20	.... do	.... do	Slack.............	.... do...............	1	23.51	235.8	98.0	3.11	5.92	6.83	......	....
21	.... do	.... do	Duff..............	Stirling No. 7 & 8 plain grate.........	1	20.78	382.6	73.6	2.55	6.21	8.11	11185	53.8
22	.... do	.... do	Pea...............	National W. T. No. 1 Murphy furnace...	2†	21.01	216.9	86.8	2.90	5.86	7.13	......	....
23	McLean	Bloomington....	Lump.............	Hor. Tub. No. 2 plain grate...............	10*	11.34	10.7	101.7	2.61	6.61	8.01	......	....
24	.... do	.... do	Lump.............	B & W No. 5 plain grate...............	1*	24.76	194.2	88.3	2.73	5.30	6.26	......	....
25	.... do	Colfax..........	Lump.............	B & W No. 1 plain grate...............	2	22.70	116.3	77.5	2.70	5.06	6.64	12025	4.06
26	Menard..........	Athens..........	Lump.............	Hor. Tub. No. 2 plain grate...............	2	11.63	11.0	102.5	2.66	6.49	7.09	......	....
27	Perry............	Du Quoin........	Lump.............	Hor. Tub. No. 1 plain grate...............	4*‡	10.66	28.6	71.5	1.80	5.51	6.49	11250	47.6
28	.... do	.... do	Lump.............	Hor. Tub. No. 2 plain grate...............	2	7.37	24.6	61.5	1.59	6.15	6.85	......	....
29	.... do	.... do	Slack.............	Hor. Tub. plain grate	1	15.96	73.9	123.2	2.93	7.10	8.60	......	....
30	.... do	.... do	Lump.............	Hor. Tub. No. 4 rocking grate......	1*	18.24	117.0	117.0	4.00	7.38	8.30	11250	63.1
31	.... do	.... do	Lump.............	B & W No. 5 plain grate...............	2*	19.59	190.3	86.5	2.68	6.57	7.52	......	....
32	.... do	.... do	Pea...............	B & W No. 2 plain grate...............	2	16.06	118.5	56.4	1.85	5.00	5.87	......	....
33	Sangamon.......	Barclay..........	Pea...............	Hor. Tub. rocking grate...............	2	21.31	118.7	.....	....	6.74	7.75	......	..
34	.... do	Dawson..........	Pea...............	B & W No. 5 & 6 plain grate...............	1	29.00	513.7	123.6	3.83	6.31	7.64	......	
35	.... do	.... do	Pea...............	National W. T. No. 4 Murphy furnace...	3	15.95	152.2	66.9	2.04	5.12	6.21	......	....
36	.... do	Divernon	Lump.............	B & W No. 2 chain grate...............	3	28.60	125.9	83.9	2.92	5.42	6.98	......	....
37	.... do	Lowder..........	Slack.............	... do...............	2	22.10	103.5	69.0	2.11	5.69	7.06	11700	....
38	.... do	Ridgely..........	Pea...............	National W. T. No. 1 Murphy furnace....	6	18.00	179.7	71.9	2.40	5.68	6.33	......	....

*Steam assumed dry. ‡Coal assumed dry. †Moisture obtained by drying coal above boiler.

TABLE IV (*Concluded*)

Number	Description of Coals: County	Description of Coals: Town	Description of Coals: Commercial Size	Type of Boiler and Grate	Number of Tests Averaged	Dry Coal per sq. ft. of Grate Surface per hr.	Horsepower Developed by Boiler	Percentage of Rated Horsepower Developed	Equiv. Evaporation From and at 212° Fahr.: Per sq. ft. of Waterheating Surface per hr.	Equiv. Evaporation From and at 212° Fahr.: Per pound of Dry Coal	Equiv. Evaporation From and at 212° Fahr.: Per pound of Combustible	B. T. U. per pound of Dry Coal	Efficiency of Boiler including Grate
					See Note	lbs.		%	lbs.	lbs.	lbs.		%
				A. S. M. E. Code No.		48	65	67	64	70	71	50	73
39	Sangamon	Riverton	Pea	National W. T. No. 4 Murphy furnace	3	19.21	205.2	82.1	2.75	6.07	6.76	......	......
40	do	do	Pea	B. & W. No. 5 & 6 Roney stoker	1	24.30	463.1	105.3	3.39	6.43	8.12	9975	62.2
41	do	do	Pea	B. & W. No. 2 chain grate	4	34.30	165.7	110.1	3.85	5.96	7.39	11152	51.7
42	do	do	Pea	do	3	31.90	185.1	123.1	4.30	6.53	7.95	11152	56.7
43	do	do	Pea	do	4	17.90	89.1	59.1	2.07	6.15	8.26	11152	53.3
44	do	do	Pea	do	4	19.90	114.9	76.6	2.67	7.11	8.93	11152	62.2
45	do	do	Pea	do	5	20.50	91.1	60.9	2.12	5.19	6.23	11287	47.0
46	do		Lump	Hor. Tub. No. 2 plain grate	1	13.00	18.3	120.7	3.13	6.81	7.83	11980	55.1
47	do		Pea	B. & W. No. 2 chain grate	2	21.81	114.6	76.4	2.66	6.17	7.44	11930	52.4
48	do		Pea	National W. T. No. 4 chain grate	1	30.52	335.8	131.3	4.61	6.13	8.21	12162	51.5
49	do		Pea	do	4	30.73	331.2	132.5	4.55	6.67	8.10	11537	55.9
50	do	Springfield	Pea	B. & W. No. 1 plain grate	2†	25.70	111.3	74.2	2.58	4.27	5.18	......	......
51	do	do	Pea	B. & W. No. 2 chain grate	2†	28.20	176.3	117.5	4.09	6.16	7.75	......	......
52	do	do	Pea	B. & W. No. 6 Roney stoker	2	21.37	238.1	101.4	3.41	6.51	7.79	12591	49.9
53	Shelby	Moweaqua	Lump	B. & W. No. 5 plain grate	1*	20.78	164.4	74.7	2.32	5.35	6.27	13026	39.7
54	Vermilion	Catlin	Screenings	Murray Hor. Tub. No. 1, 2, 3. rocking grate	1	11.27	100.1	66.7	1.58	6.19	8.15	12369	48.3

55	.... do	Fairmount	Screenings	B. & W. No. 2 plain grate	1	30.67	230.1	109.6	3.51	5.08	5.95	12413	39.5
56	.... do	Muncie	Slack	Hor. Tub. No. 2 & 3 plain grate	1‡	13.62	107.9	63.5	1.76	6.07	7.50	......	......
57	.... do	Oakwood	Lump	Stirling No. 7 & 8 plain grate	1	25.42	497.6	95.7	3.32	6.63	8.07	12503	51.0
58	.... do	.... do	Screenings	...... do	1	25.09	507.4	97.6	3.38	6.85	8.39	11427	57.9
59	.... do	.... do	Screenings	B. & W. plain grate	1	17.91	166.9	61.2	2.01	5.02	6.59	10299	47.1
60	.... do	.... do	Screenings	Heine chain grate	2	23.94	382.7	109.3	4.18	7.66	9.61	11067	66.8
61	.... do	.... do	Pea	B. & W. No. 6 Roney stoker	2	22.40	230.9	98.3	3.39	7.15	8.58	13251	52.1
62	Williamson	Carterville	W. Pea & Duff	...... do	3	19.96	240.2	102.2	3.52	8.14	8.89	13108	58.6
63	.... do	Herrin	New Ky. Pea	B. & W. No. 2 chain grate	3	32.93	196.0	130.7	4.55	7.34	8.74	12769	55.5
64	.... do	.... do	... do W. Screen	...... do	1	31.60	210.3	140.2	4.88	7.50	8.89	13156	55.0
65	.... do	.... do	... do W. Screen	B. & W. No. 5 & 6.. Roney stoker	1	26.55	620.7	132.1	4.55	7.75	9.21	12364	60.5

*Steam assumed dry. ‡Coal assumed dry. †Moisture obtained by drying coal above boiler.

NOTE: Column headed "Number of Tests Averaged" gives the number of boiler tests, the average of whose results is recorded in the Table.

the results of the ten highest tests together with the single highest result obtained. The basis of comparison is the equivalent pounds of water evaporated from and at 212° F. per pound of dry coal. The same table also contains the average of the results of six tests with Illinois coals made by the Boiler Division of the Fuel Testing Plant of the United States Geological Survey at St. Louis. It is interesting to note that in these latter tests in which hand-firing and plain grates were used, the results obtained are better than any of the others recorded, including the results of tests in which mechanical stokers were used. This fact may be taken to indicate that the maximum efficiency of Illinois coals is rarely obtained under present average conditions. It is probable that with a closer study of furnace conditions, even these results may be improved. The general tests reported in Tables 3 to 5 include a number of trials made with special objects in view. Several of these trials are described as follows:

1. Tests of a small horizontal tubular boiler of 40 horsepower, to determine its performance with varying rates of combustion. The results of these tests are given below.

RESULTS OF A BOILER TRIAL SHOWING EFFECTS OF RATE OF COMBUSTION ON THE PERFORMANCE OF HORIZONTAL TUBULAR BOILER

Dry coal per square foot of grate surface per hour	6.80	9.30	11.00	12.00	14.00
Equivalent evaporation from and at 212° F. per pound of dry coal	6.20	6.55	6.57	6.37	5.75
Horse-power in per cent of rated capacity (40)	52.50	87.50	107.50	115.00	122.50
Temperature of escaping gases	432.00	447.00	501.00	516.00	553.00

The same kind of coal was used in all these tests, and conditions remained nearly constant. It is evident that the maximum results were obtained with the boiler running at its rated capacity, with the flue gas temperature about 500° F. With an increase in the rate of combustion, the capacity and flue gas temperature increased and the evaporation dropped off.

2. Tests to determine the effect of soot deposits on the evaporation of a small horizontal tubular boiler. These tests were made on the same boiler as the preceding series and with results as follows:

RESULTS OF BOILER TRIALS MADE TO DETERMINE THE EFFECT OF SOOT DEPOSITS ON THE EVAPORATION OF A HORIZONTAL TUBULAR BOILER

	First Series (5 days) Soot allowed to remain on tubes	Second Series (5 days) Tubes cleaned each morning	Third Series (5 days) Soot allowed to remain on tubes
Equivalent evaporation from and at 212° F. per pound of dry coal	6.20	7.04	6.23
Dry coal per sq. ft. of grate surface per hour	13.40	9.09	13 40
Horse power in per cent of rated capacity	111.00	99.00	115 00
Temperature of escaping gases	627.00	546 00	698.00

It is evident from the results that the effect of the soot deposit on the evaporation is not very marked. It is interesting to note that in the first and last series, in which the soot was allowed to remain on the tubes, the soot burned upon reaching a certain thickness, leaving but a very thin layer. In all three series the conditions were held as nearly constant as possible, although in the second series the load fluctuated somewhat on the different days.

TABLE V COMPARISON OF RESULTS OF BOILER TESTS WITH ILLINOIS COALS ON HORIZONTAL TUBULAR AND WATER-TUBE BOILERS

Type of Boiler and Grate	No. of Tests Aver.	No. of Coals Aver.	Aver. Force of Draft	Aver. Flue Gas Temp.	Dry Coal per sq. ft. of Grate Surface Per hr.	Horse-power		Equiv. Evap. F. and A. 212°			B. T. U. Per lb. of Dry Coal	Eff. of Boiler and Grate
						Develop'd by Boiler	Per cent of rating Dev'p'd	Per sq. ft. of Heating Surface per hr.	Per lb. of Dry Coal	Per lb. of Combustible		
A. S. M. E. Code No.			12	21	48	65	67	64	70	71	50	73
Water-Tube Roney stoker	9	5	.214	605	22.7	305	105	3.57	7.32	8.53	13031	51.2
	9	5	.214	605	22.7	305	105	3.57	7.32	8.53	13034	51.2
	Highest Single	1	.166	656	26.5	....	132	4.55	7.75	9.21	12364	60.5
Water-Tube chain grate	46	9	.493	521	27.2	180	98	3.43	6.29	7.82	11562	52.5
	Highest											
	10	4	.571	507	26.1	202	106	3.76	7.33	9.01	11821	59.9
	Highest Single	1	.710	592	23.9	....	109	4.18	7.66	9.61	11067	66.9
Hor. Tubular rocking grate	6	4	.323	473	20.5	121	113	3.70	6.81	7.95	11809	55.7
	6	4	.323	473	20.5	121	113	3.70	6.81	7.95	11809	55.7
	Highest Single	1	.257	519	18.2	117	117	4.00	7.38	8.30	11250	63.4
Hor. Tubular plain grate	45	10	.267	534	11.5	45	95	2.15	6.38	7.48	11532	53.4
	Highest	5	.354	542	13.4	52	123	3.16	6.91	7.85	11797	56.6
	10											
	Highest Single	1	.405	549	13.6	....	130	3.37	7.05	7.78	11130	59.6
Water-Tube plain grate	39	19	.400	509	20.6	176	79	2.62	5.75	6.67	11608	47.8
	Highest	4	.404	552	21.6	220	92	3.28	6.64	7.85	11728	51.7
	10											
	Highest Single	1	.790	616	25.1	507	98	3.38	6.85	8.39	11427	57.9
Water-Tube Murphy Furnace	18	5	.530	488	18.3	189	76	2.53	5.87	6.64	......	....
	Highest	4	.516	481	19.1	205	82	2.75	6.11	6.92	......	....
	10											
	Highest Single	1	.580	481	18.4	205	82	2.76	6.36	7.09	......	....
U. S. G. S. Tests Water-Tube plain grate	6	4	.527	595	22.3	198	94	3.36	7.55	8.84	12293	59.3
	Highest Single	1	.580	637	21.2	201	96	3.41	8.04	9.53	12857	60.4

3. Tests of a water-tube boiler with chain grate stoker to determine the relative economy of a 6-inch and an 8-inch fuel bed with various rates of combustion.

The results of these tests are best shown by the curves in Fig. 9.

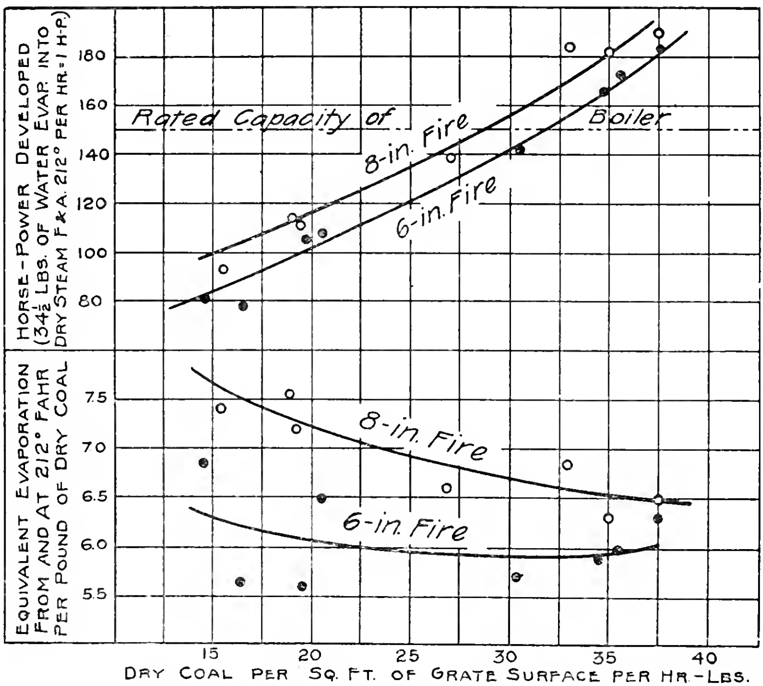


FIG. 9 CURVES SHOWING THE RELATIVE ECONOMY OF A 6-INCH AND 8-INCH FUEL BED IN A CHAIN GRATE STOKER

They show that under the conditions of the test, the 8-inch fire was the more efficient, giving an equivalent evaporation per pound of dry coal 10 per cent greater than the 6-inch fire, when operating at the rated capacity of the boiler. The same coal was used throughout this series. The averages of the results of these tests are reported in Tables III and IV, viz., Nos. 41, 42, 43 and 44. In Figs. 10, 11 and 12 are shown a few of the characteristic results of boiler trials made on water-tube boilers with chain grate stokers. These diagrams are plotted from the results of 38 trials, and each point on the diagram represents the average of 5 trials. It is safe to assume, therefore, that the results represent average conditions.

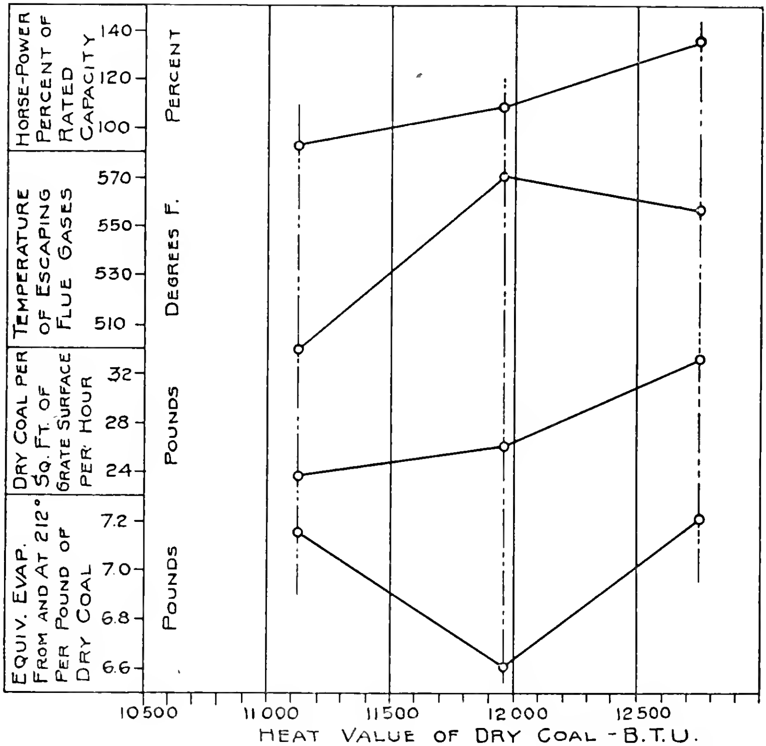


FIG. 10 CHART SHOWING VARIATION IN BOILER PERFORMANCE WITH COALS OF DIFFERENT HEAT VALUE

Fig. 10 shows the results of trials, in which coals of highest, lowest and mean heat values were used, plotted on a basis of heat value. The sudden drop in the equivalent evaporation per pound of dry coal, with coals of low and medium heat value is no doubt due to the large increase in the flue gas temperature with constant rate of combustion and capacity. With coals of medium and high heat value the equivalent evaporation increases with increasing rate of combustion and capacity, the flue gas temperature remaining constant. It is evident from the diagram that the effect of the heat value of the coal is not very marked, a large increase, however, other conditions remaining constant, causing an increase in the evaporation per pound of coal, as will be seen in Fig. 12.

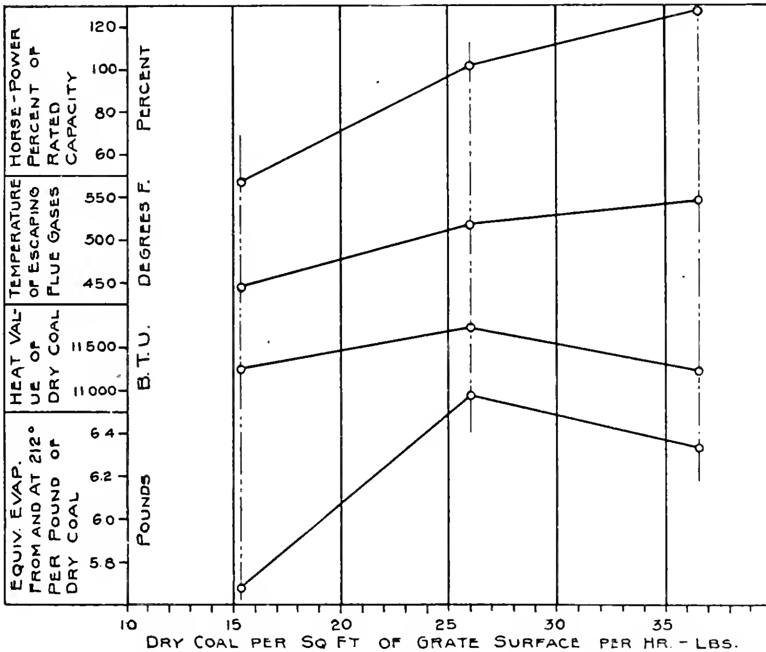


FIG. 11 CHART SHOWING VARIATION IN BOILER PERFORMANCE WITH VARYING RATES OF COMBUSTION

In Fig. 11 the results of a boiler trial are plotted on a basis of rate of combustion. It is evident from the diagram that the equivalent evaporation per pound of dry coal increases with the rate of combustion until the capacity reaches 100 per cent, or the rated capacity, the heat value of the coal remaining approximately constant, the flue gas temperature at this point being 500° F. With a further increase in the rate of combustion the capacity and flue gas temperature still increase but the equivalent evaporation per pound of coal decreases. This curve, if it may be called such, might be named the characteristic curve of the boiler, and is important because it shows the rate of combustion above which the evaporation per pound of coal decreases.

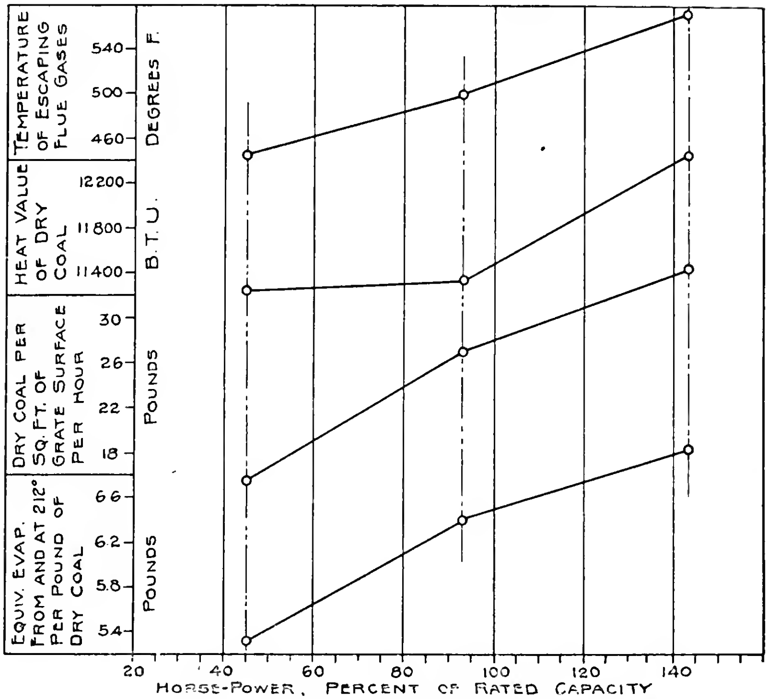


Fig. 12 Chart Showing Variation in the Performance of a Boiler Working at Different Capacities

The effect of capacity on the evaporation is shown by the diagram in Fig. 12. It is seen that here as in the previous figure the evaporation per pound of dry coal again increases with an increase in the capacity due to an increased rate of combustion. However, instead of attaining a maximum at 100 per cent capacity, it increases with a further increase of capacity and rate of combustion. At first sight this seems contradictory to the previous diagram, Fig. 11; however, it is evident that this increase is not due to this further increase in the rate of combustion and capacity, but is due to the sudden increase in the heat value of the coal (about 10 per cent) used.

V Arrangements For Future Fuel Tests

In publishing this bulletin it has been the desire to record the results of the most important tests of boilers fired with Illinois

coals, that have been made up to date. During the year 1906 the Engineering Experiment Station at the University purchased and installed a plant designed especially for conducting a series of fuel tests of Illinois coals. The plant consists of a 210 H. P. Heine water-tube boiler together with a Green chain grate stoker and a Sturtevant economizer and induced draft fan and engine. This boiler is a duplicate of the boilers used by the United States government in the fuel tests in progress at St. Louis under the direction of the United States Geological Survey. It was thought that in this way the fuel tests here at the University would be in a measure comparable with the tests made by the government on coals from all parts of the United States.

The rapid growth of the industrial interests of Illinois demands a careful study of the great fuel supply, and no effort should be spared in the introduction and promulgation of improved methods and processes in the production, treatment and consumption of its coal. In the tests of Illinois coals which it is now proposed to make, less attention will be paid to routine boiler tests, familiarly known as such, and more attention will be given to a scientific study of fuel treatment before burning and to a study of those furnace constructions and conditions which give promise of maximum results. In order that future tests may be conducted along lines which will meet with the general approval of the various interests of the state, a Conference Committee on Fuel Tests has been appointed consisting of the members named below and representing the organizations indicated:

H. Foster Bain, Director State Geological Survey, Urbana, Ill., representing the State Geological Survey;

A. Bement, Consulting Engineer, Chicago, the Western Society of Engineers;

Edwin H. Cheney, President Fuel Engineering Co., Chicago, the Building Managers' Association of Chicago;

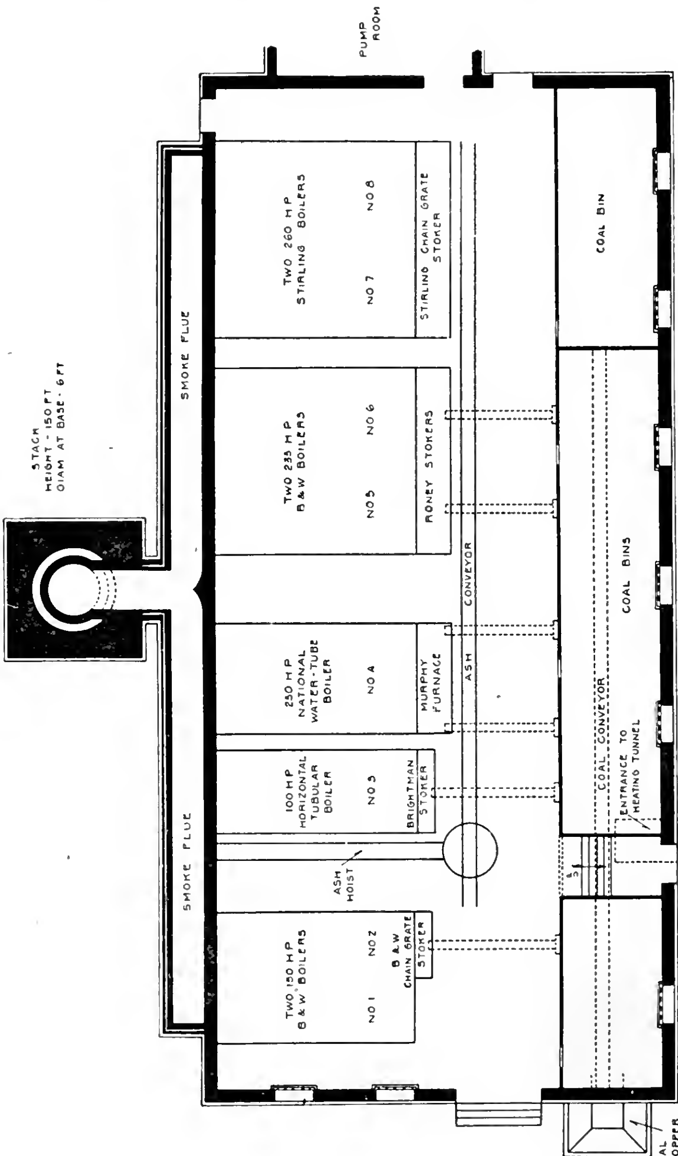
F. H. Clark, Gen. Supt. Motive Power Burlington Road, C. B. & Q. Ry., Chicago, the Western Railway Club;

Adolph Mueller, President H. Mueller Mfg. Co., Decatur, Ill., the Illinois Manufacturers' Association;

Carl Scholz, President Coal Valley Mining Co., Chicago, the Illinois Coal Operators' Association;

A. V. Schroeder, Decatur Railway and Light Company, Decatur, Ill., the State Electric Light Association;

Wm. L. Abbot, Chief Operating Engineer, Chicago Edison Co., Chicago, the Board of Trustees University of Illinois;



PLAN OF CENTRAL HEATING STATION
UNIVERSITY OF ILLINOIS
SCALE 0 5 10 15 FEET

L. P. Breckenridge, Director Engineering Experiment Station, University of Illinois, Urbana, Ill.

Reference has been made to the government fuel tests at St. Louis. It should be stated that the work of the boiler division of these tests has been carried on under the direction of the Director of the Illinois Engineering Experiment Station, who will also have charge of the tests made at the University of Illinois. Copies of Professional Paper No. 48, containing a report on the operations of the government coal testing plant at St. Louis may be obtained upon application to a member of Congress or to the Director of the United States Geological Survey, Washington, D.C.

It is not the intention of this bulletin to discuss the subject of fuel testing. A future bulletin will take up that subject and will also describe in full the plant provided for such tests at this University. Attention is called, however, to the facilities now offered for this important work. It is hoped that mine owners and manufacturers will find it advantageous to cooperate with the Engineering Experiment Station in the proposed tests. The Station Staff will always be glad to receive such suggestions concerning this work as those interested may desire to offer.

VI Chemical Analysis and Heat Values of Illinois Coals

By S. W. Parr, Professor of Applied Chemistry

The accompanying results of chemical analyses of Illinois coals may be divided into three classes: first, those which were directly connected with the boiler tests conducted by the department of Mechanical Engineering, and which are listed in a separate table, covering such work from the year 1894 to 1905; second, in connection with thesis work by Mr. F. C. Koch in 1901, there were assembled by him the results of all analyses of Illinois coals which had been made by the department of Chemistry previous to that date. These results were published together with his own work in a bulletin through the courtesy of Secretary Ross of the Bureau of Labor Statistics in the report of that Bureau in 1902. They are designated in the tables by the letters B. L. S. The third series of results comprises the work on one hundred fifty samples of Illinois coal collected in 1904 and published in a separate bulletin in connection with the exhibit of mines and min-

erals at the St. Louis Exposition. These results are designated in the tables by S. W. P. The sum total of data which has thus resulted, while of a somewhat desultory nature, constitutes a very considerable contribution to our knowledge of the constituents of Illinois coals. It is to be noted that the processes employed in connection with this series were confined almost exclusively to the method of proximate analysis. In the future the more exacting demands of modern methods will require extended data such as are furnished by both proximate and ultimate analysis, including of course the determination of calorific units. It may be well therefore, at the present time, to assemble the information obtainable up to the present date, compiling it as in the accompanying tables, and also to discuss briefly some of the terms which are used in connection with the chemical work on coals. The chemist employs terms and processes which are also used by the engineer, but it does not always follow that their use of terms is in accord.

Moisture.—Moisture in coal is constantly undergoing a change as to quantity. The percentage contained at the time of breaking out the coal from the vein is greater than at any subsequent stage of its history, unless possibly it be under the conditions of rain or snow or drenching with the hose. Some of this moisture which is normally contained in the coal is lost when the coal is exposed to the air, being in this respect like water which has been poured upon the coal. But there remains moisture in the coal after air-drying and which is removed only at the temperature of boiling water. This moisture is described as hygroscopic. If now the chemist works upon a sample which is overcharged with moisture, as is the condition when the sample is freshly mined, it will be constantly losing in weight and modifying his results. Similarly, if he works upon a sample which has been completely dried in the oven, it will have great avidity for moisture and be constantly gaining in weight throughout his work. He, therefore, proceeds in his determinations, as a rule, with the coal in that condition which is least affected by external conditions, viz., in the air-dry state with the normal amount of hygroscopic moisture present, but without the excess of water, which might be termed water of saturation.

Therefore, we have three distinctly different conditions: first, the wet coal; second, the air-dry coal; and third, the oven-dry state. The engineer, however, not having to do with the condi-

tions under which the chemist works, recognizes only the two phases, either the wet or dry, and by this latter term he means the oven-dry state. The failure on the part of the engineer and the chemist to recognize these terms often leads to misinterpretation of results. The chemists, therefore, should agree to such use of terms relating to water as have become firmly established in engineering literature: viz., that dry coal refers to moisture free coal or to the oven-dry state, and second, that wet coal refers to the condition as received or previous to any process of air-drying, and that it is one or the other of these conditions that is of interest to the engineer, regardless of how important it may be to the chemist to proceed upon the basis of the air-dry condition.

It may not be out of place further to indicate how results may be transferred from one basis to the other. It is not an uncommon practice for the chemist to report his results on the air-dry basis, in which case he should also report the amount of moisture lost upon air drying, provided his sample comes to him sealed in such a way as to make this factor possible. Suppose, for example, that the loss of moisture upon air-drying is 4 per cent, then all his results reported on the air-dry basis would be changed to the wet coal basis by multiplying each by 96 per cent; not by dividing by 104 per cent as is often erroneously done. This will make small difference in a constituent which has a low percentage factor, but the error is very considerable in a factor like the fixed carbon which is from 40 to 50 per cent. This may seem like a simple arithmetical problem to mention in this connection, but it is one not always correctly interpreted.

Conversely, if it is desired to change factors to the dry coal basis, each factor should be divided by 100 minus the percentage content of water in that condition from which the transfer is being made. For example, if we are calculating this coal from the *air-dry* state, supposing it to have 6 per cent of moisture present, each factor should be divided by 94 per cent, but it should be noted that if we are calculating from the *wet-coal* condition our divisor will not be 100 per cent minus the sum of the two factors, 6 and 4, as in the above illustration, but 100 minus 96 per cent of 6 plus 4, or 90.24. Here again is a not uncommon place for stumbling in what might seem to be a simple arithmetical problem.

Volatile Matter.—When coal is subjected to high temperature out of contact with the air, a considerable amount is driven off as

volatile matter. This includes, also, of course, any moisture in the sample, if we start with a portion which has not been dried in the oven. Now an even greater discrepancy in the use of terms has come into use in connection with this constituent than is the case with different forms of water. One of the oldest terms is that of volatile carbon. This is both incorrect and meaningless because carbon is not volatile, and because the constituents of this material are numerous and complex. The term that is perhaps most frequently met designates this material as volatile combustible. This again is incorrect and misleading, as this material in the ordinary bituminous type of coal has from one-third to one-half of its weight made up of non-combustible material. It is evident, therefore, that the only proper term among those commonly in use for this constituent is that of *volatile matter.* The only restriction indeed in connection with this term is to understand, as is the uniform custom, that the moisture of the coal is not included. A word may be in place here in connection with a term which is occasionally met, and is likely to be more frequently used than formerly. This term is intended to designate that part of the volatile matter which does not burn. This constituent is sometimes referred to as "water of composition". It is not included in any of the results listed in the following tables, and hence its use does not enter into any of the discussions in this bulletin. It is noted in this connection, however, in order that it may not be confused with any of those terms which are intended to designate the water in its ordinary form and which are capable of being driven off at the temperature of boiling water. This property does not belong to the water of composition, as this substance like the other part of the volatile matter, requires a red heat for its dissociation.

Fixed Carbon and Ash.—Concerning these constituents there is no disagreement as to the use of terms unless it be the occasional use of the word coke. Coke in its proper and technical sense should apply to the residue including the ash after subjecting the coal to destructive distillation. It is, therefore, not proper to designate the fixed carbon as coke, though it would be proper, of course, to use the term "coking carbon" in this connection. The preferable term and the one commonly employed, however, for this material is that of fixed carbon.

Methods of Analysis.—The methods of analysis employed are those in common use and their description is so easily accessible

that no repetition is necessary here. Reference may be made to the report of the committee of the American Chemical Society on coal analysis.[1]

Calorific Value.—The determination of heat units in coals is, of course, a necessity in connection with any well conducted boiler test. Two systems of units are employed, viz., the kilo calories and the British Thermal Units, designated as B. T. U. Each unit is the measure of heat imparted to the water by an equal weight of coal. They would, therefore, be identical if it were not for the fact that the one is read on the Centigrade scale and the other on the Fahrenheit scale. The transfer, therefore, of calories per kilo over to B. T. U. per pound is effected by multiplying by the ratio of 9:5 or 1.8.

There are four types of instruments in use for measuring the heat value of coals. The first and most elaborate is the Mahler instrument which has numerous modifications as to detail, but which embodies the use of a steel bomb capable of maintaining oxygen from twenty to twenty-five atmospheres pressure. The next in the order of time is the Fisher calorimeter which burns the sample of coal in a small chamber supplied with oxygen at atmospheric pressure. The third type may be designated as the L. Thompson calorimeter, wherein the coal is mixed with a chemical which in itself supplies the oxygen for carrying on the combustion and in which the gaseous products are allowed to bubble up through the water, thus imparting their heat to the liquid. The fourth type may be designated as the Parr calorimeter which also employs a chemical having its own supply of oxygen, but which absorbs the gaseous products, thus retaining all the heat of the reaction for more accurate measurements by the thermometer. Of the second and third types, it may be said that owing either to incompleteness of combustion or to loss of heat by transmission of the gases, results are obtained which are not of sufficient accuracy for reliable work. Results from the Thompson calorimeter are reported by certain authorities to admit of variations amounting to 15 per cent. The Mahler type of calorimeter is accurate when operated by one thoroughly familiar with such processes. The Parr calorimeter is the one used in connection with the analyses in these tables of all coals made since 1900, and is now the instru-

[1]Jour. Am. Chem. Soc. Vol. XXI. p. 1130.

ment most commonly used in technical work. A brief description of this apparatus follows:

Fig. 13 shows the relative position of parts. The can A.A. for the water has a capacity of 2 litres. The insulating vessels B.B. and C.C. are of indurated fiber. The charge of coal and chemical is put in the cartridge D. Upon ignition, the heat generated is imparted to the water and the rise in temperature is indicated on the finely graduated thermometer T. The cartridge or bomb rests on the pivot F and is made to revolve, and by aid of the small turbine wings attached effects a complete circulation of the water and equalization of temperature.

The reaction accompanying the combustion may be represented by the equation:

$$\underset{\text{Sod. perox.}}{56Na_2O_2} + \underset{\text{Coal}}{C_{25}H_{18}O_3} = \underset{\text{Sod. carb.}}{25\ Na_2CO_3} + \underset{\text{Sod. hydrate}}{18\ NaOH} + \underset{\text{Sod. oxide}}{22\ Na_2O}$$

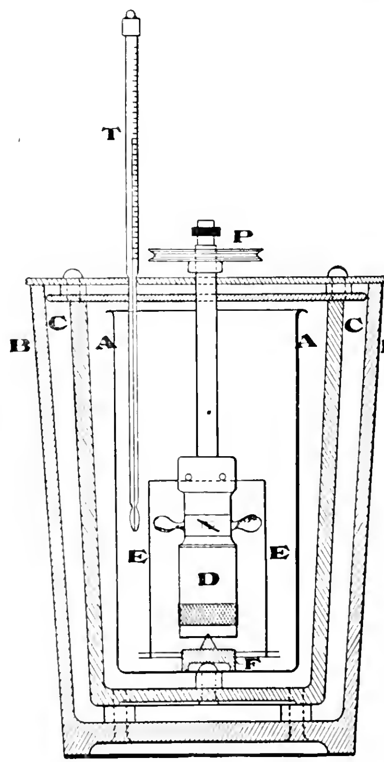


FIG. 13

With certain substances such as coke, anthracites, petroleums, etc., a more strongly or vigorously oxidizing medium is needed than exists in the peroxide alone. This may be secured by various additions. The most effective are: A mixture of potassium chlorate and nitrate in the proportion of 1 to 4 and this mixture used in the ratio of 1 to 10 of the sodium peroxide; another effective mixture is an addition of potassium persulphate in the ratio of 1 to 10 of the sodium peroxide. Other substances facilitate the oxidation, notably ammonium salts and certain organic substances, as tartaric or oxalic acid, benzoic acid, etc. In the work on Illinois coals, while ordinarily no extra chemical would be necessary, still in certain cases, such as extra slaty coals and coals with excessive volatile matter, and also to guard against variations in the quality of the sodium peroxide, a mixture as first described above, of chlorate and nitrate, has uniformly been used throughout these tests.

Further extension of the use of the instrument to other types of coal and to petroleum has made it necessary to extend still further the oxidizing power of the chemicals employed beyond what is afforded by the chlorate mixture. In addition to this the use of the residue for determining the total carbon and sulphur has made it highly desirable in such additional chemicals to avoid the use of compounds containing carbon or sulphur. To meet these conditions, the so-called "boro-mixture" has been devised. It consists of:

Boric acid..............	11 parts
Potassium chlorate........................	4 parts
Magnesium powder........................	1 part

Its correction factor is found by trial with a pure chemical of known heat value. such as napthalene or by burning with a coal whose heat value is already accurately known. This mixture has the further advantage of carrying on a combination with material so low in carbonaceous matter as to be non burning by ordinary methods, such as ashes and coals of very high ash content.

Still further modifications relate to the bomb as shown in Fig. 14, and have to do mainly with the avoidance of screw threads on the interior of the combustion chamber, especially in the upper part, where particles tend to lodge and thus escape combustion; also in jacketing the lower part of the chamber to avoid direct contact with the water, thereby avoiding rapid

cooling of the parts and extending somewhat the period of high temperature, thus securing a more perfect combustion.

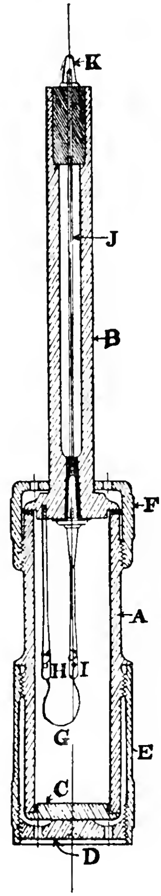


FIG. 14

Calorific Values By Calculation.—Numerous methods for calculating the calorific value of coal have been proposed, but no method can be said to have any value which is not based on a knowledge of the percentage constituents of the total carbon, available hydrogen and sulphur. Even under these conditions the results by calculation are not always in agreement with the indicated results by means of the calorimeter, and in any event, of course, results from proximate analysis do not furnish the neces-

sary data for this calculation. When this method is used the Dulong formula is considered the most nearly accurate and is as follows:

$$\text{Cal.} = 8080 + 34{,}500\ \text{H} + 2250\ \text{S}$$

In the results here recorded the necessary factors were not always available for applying this formula, but it is the one used wherever calorific values by calculation are included.

TABLE VI CHEMICAL ANALYSIS AND HEATING VALUES OF ILLINOIS COALS USED IN STEAM BOILER TRIALS AT UNIVERSITY OF ILLINOIS 1894-1905

No.	Source of Coal		Description of Coal	Date of Analysis	Boiler Test No.	Proximate Analysis—Air-Dry Coal					B. T. U. per lb. of Total Dry Coal
	County	Town				Fixed Carbon	Volatile Matter	Moisture	Ash	Sulphur	
1	Christian	Pana	Slack	June '94	1	.....	.....	.....	.....	.....	.....
2	Christian	Pana	Pea	June '94	2	.....	.....	.....	.....	.....	.....
3	Christian	Pana	Screenings	June '94	3	.....	.....	.....	.....	.....	.....
4	Christian	Pana	Lump Slack	June '94	4	.....	.....	.....	.....	.....	.....
5	Coles	Paradise	Lump	Feb. 26 '97	5	48.33	34.56	10.72	6.39	.....	11,430
6	Gallatin	Junction	Pea	Mar. 20, '99	43,52	43.52	37.04	9.91	10.33	3.65	.....
7	Macon	Niantic	Nut	Jan. 16, '95	7	40.55	34.25	4.44	20.79	.....	11,203
8	Macoupin	Mt. Olive	Lump	Feb. '97	8	.....	.....	.....	.....	.....	.....
9	Madison	Glen Carbon	Lump	May 13, '01	9	40.66	39.13	7.85	12.36	4.87	12,522
10	Marion	Odin	Lump	Apr. '94	10	.....	.....	.....	.....	.....	.....
11	Marion	Odin	Lump	Apr. '95	11	48.09	34.90	7.10	9.91	.....	12,110
12	Marion	Odin	Pea	June '96	12	42.30	37.93	5.09	14.68	.....	11,569
13	Marion	Odin	Pea	Oct. 6, '96	13	45.23	41.25	7.28	6.24	.....	11,070
14	Marion	Odin	Pea	Jan. 16, '97	14	39.54	31.95	6.48	22.03	.....	.....
15	Marion	Odin	Lump	Mar. 6, '95	15	44.45	37.73	6.32	11.56	.....	.....
16	Marion	Odin	Lump	Jan. '95	16	46.02	40.25	6.20	7.53	.....	12,665
17	Marion	Odin	Pea	Mar. 14, '99	17	46.70	34.65	6.70	11.95	3.43	.....
18	Marion	Odin	Lump	Nov. 11, '96	18	45.10	37.06	8.02	9.83	.....	11,880
19	Marion	Odin	Lump	June '94	19	.....	.....	.....	.....	.....	.....
20	Marion	Odin	Slack	Dec. 9, '96	20	42.26	34.31	8.00	15.43	.....	12,130
21	Marion	Odin	Duff	Mar. 28, '05	21	45.11	31.79	7.21	15.86	2.12	11,185
22	Marion	Odin	Pea	Jan. 26, '99	22	46.70	34.65	6.70	11.95	3.43	.....
23	McLean	Bloomington	Lump	Jan. '95	23	.....	.....	.....	.....	.....	.....
24	McLean	Bloomington	Lump	Dec. '94	24	43.50	43.90	3.80	8.80	.....	.....
25	McLean	Colfax	Lump	May '02	25	42.58	41.35	8.02	8.05	1.80	12,025
26	Menard	Athens	Lump	Mar. '97	26	41.95	35.18	12.11	10.76	.....	13,824
27	Perry	Du Quoin	Lump	Oct. '95	27	47.53	35.77	7.59	9.11	.....	12,174
28	Perry	Du Quoin	Lump	June 16, '98	28	48.59	33.15	8.13	9.21	.....	.....
29	Perry	Du Quoin	Slack	Apr. '98	29	41.60	35.95	6.05	16.40	5.14	11,761
30	Perry	Du Quoin	Lump	Feb. '95	30	45.10	39.81	7.43	7.66	.....	12,174
31	Perry	Du Quoin	Lump	Feb. '95	31	45.10	39.81	7.43	7.66	.....	12,174
32	Perry	Du Quoin	Pea	Mar. 12, '01	32	.....	.....	.....	.....	.....	.....
33	Sangamon	Barclay	Pea	Apr. '98	33	45.19	38.15	3.76	12.90	.....	.....
34	Sangamon	Dawson	Pea	Mar 13, '99	34	41.40	33.65	12.54	12.41	5.63	.....
35	Sangamon	Dawson	Pea	Mar. 4, '99	35	41.40	33.65	12.54	12.41	5.09	.....
36	Sangamon	Divernon	Lump	May 6, '01	36	38.59	34.72	8.69	18.00	6.03	11,239
37	Sangamon	Lowden	Slack	Apr. '04	37	45.02	35.00	6.92	12.55	1.73	11,700
38	Sangamon	Ridgely	Pea	Feb. '99	38	40.04	37.33	9.80	12.83	4.19	.....

39	Sangamon........	Riverton..........	Pea...........	Mar. ......'99	39	40.57	36.51	8.83	14.10	4.22	.....
40	Sangamon........	Riverton..........	Pea...........	Jan ......'04	40	33.98	36.27	8.23	21.52	....	9,975
41	Sangamon........	Riverton..........	Pea	Dec. ......'03	41	43.20	36.96	3.38	16.46	1.01	11,152
42	Sangamon........	Riverton..........	Pea...........	Jan. ......'01	42	43.20	36.96	3.38	16.16	1.01	11,152
43	Sangamon........	Riverton..........	Pea...........	Feb. ......'04	43	43.20	36.96	3.38	16.46	1.01	11,152
44	Sangamon........	Riverton..........	Pea...........	Mar. ......'01	44	43.20	36.96	3.38	16.16	1.01	11,152
45	Sangamon........	Riverton..........	Pea...........	Jan. ......'04	45	43.20	36.96	3.38	16.46	4.10	11,287
46	Sangamon........	....	Lump..........	Feb. ......'97	46	40.57	35.41	12.47	11.52	....	11,980
47	Sangamon........	....	....	Apr. ......'04	47	43.52	37.01	9.11	10.33	3.65	11,930
48	Sangamon........	....	....	Jan. ......'05	48	41.57	36.56	8.79	13.08	3.12	12,162
49	Sangamon........	....	....	Apr. ......'05	49	41.33	32.28	9.19	17.20	3.76	11,537
50	Sangamon........	Springfield........	Pea...........	Apr. ......'01	50	.....	.....	.....	.....	.....	.....
51	Sangamon........	Springfield........	Pea...........	Apr. ......'01	51	.....	.....	.....	.....	.....	.....
52	Sangamon........	Springfield........	Pea...........	Nov. ......'05	52	42.44	36.59	5.12	15.55	6.14	12,591
53	Shelby...........	Moweaqua..........	Lump..........	Jan. 19, '05	53	43.75	39.58	9.18	7.49	.....	13,026
54	Vermilion........	Catlin............	Screenings....	Mar. ......'05	54	43.40	29.62	7.41	19.57	2.12	12,369
55	Vermilion........	Fairmount.........	Screenings....	Dec. ......'96	55	39.85	36.16	10.67	13.02	.....	12,413
56	Vermilion........	Muncie............	Slack.........	Nov. 26, '95	56	.....	.....	.....	.....	.....	.....
57	Vermilion........	Oakwood...........	Lump..........	Mar. ......'05	57	45.13	37.40	6.80	10.67	3.10	12,503
58	Vermilion........	Oakwood...........	Screenings....	Apr. ......'05	58	42.19	35.55	8.24	11.02	3.23	11,427
59	Vermilion........	Oakwood...........	Screenings....	Apr. ......'05	59	38.88	33.43	6.02	21.67	3.21	10,299
60	Vermilion........	Oakwood...........	Screenings....	May ......'05	60	41.76	35.25	6.08	16.91	3.14	11,067
61	Vermilion........	Oakwood...........	Pea...........	Nov. 25, '05	61	41.47	39.85	5.62	13.06	3.63	13,251
62	Williamson.......	Carterville.......	W. Pea, Duff..	Nov. ......'05	62	55.52	32.40	3.33	8.76	1.97	13,108
63	Williamson.......	Herrin............	New Ky. Pea..	Apr ......'04	63	53.32	33.10	2.94	10.61	1.42	12,769
64	Williamson.......	Herrin............	N. Ky. W. Scr.	Apr. ......'01	64	53.32	33.10	2.94	10.64	1.42	13,156
65	Williamson.......	Herrin............	N. Ky. W. Scr.	Feb. ......'01	65	53.26	31.12	5.00	10.62	.....	12,361

TABLE VII Chemical Analysis and Heating Values of Illinois Coals

No.	Source of Sample		Description		Date of Analysis	Analysis Obtained from	Proximate Analysis—Air-Dry Coal					B. T. U. per lb. of total Dry Coal
	County	Town	Size	Geol. Seam			Fixed Carbon	Volatile Matter	Moisture	Ash	Sulphur	
1	Adams	Elm Grove	Drill Core		Mar. 28 '06	Chem. Dept.	47.00	35.83	4.62	12.55	2.45	12,966
2	Adams	Elm Grove	Drill Core		Mar. 28 '06	Chem. Dept.	50.57	36.89	3.52	9.02	2.68	13,915
3	Bureau	Ladd	W. Nut	2	'04	S. W. P. '04	45.67	38.30	7.04	8.99	2.10	12,217
4	Bureau	Ladd	W. Slack	2	'04	S. W. P. '04	46.75	38.61	6.60	8.04	2.70	14,117
5	Bureau	Lombardville	Vein Sample		'78	B. L. S. '02	51.74	31.38	9.42	7.46	2.46	......
6	Bureau	Spring Valley	W. Screen		May '99	B. L. S. '02	39.01	35.58	12.40	13.01	2.81	......
7	Champaign	Ivesdale	Drill Core		Jan '02	B. L. S. '02	49.27	35.89	5.68	9.16	......	12,638
8	Christian	Assumption			'89	B. L. S. '02	50.10	41.20	3.90	4.80	......	13,598
9	Christian	Assumption	Block			B. L. S. '02	47.86	37.76	7.25	7.13	2.94	......
10	Christian	Assumption	Lump			B. L. S. '02	43.56	37.24	7.97	11.23	5.21	......
11	Christian	Assumption	Nut	1	'04	S. W. P. '04	48.16	38.30	8.46	5.08	1.58	13,739
12	Christian	Assumption	Slack	1	'04	S. W. P. '04	43.28	36.26	7.74	12.72	2.60	12,621
13	Christian	Pana			'89	B. L. S. '02	46.95	36.37	7.22	9.46	......	12,513
14	Christian	Pana	Slack		Mar. '98	B. L. S. '02	39.35	35.45	8.55	16.65	4.77	10,727
15	Christian	Pana	Nut		Dec. '02	B. L. S. '02	46.04	39.43	5.30	9.23	......	12,522
16	Christian	Pana	Screen		Apr. 17 '06	Chem. Dept.	39.11	33.75	8.76	18.38	4.10	11,233
17	Christian	Pana	Lump	6	'04	S. W. P. '04	41.28	41.42	9.00	8.30	3.20	12,849
18	Christian	Pana	Slack	6	'04	S. W. P. '04	37.44	35.84	8.06	18.66	3.45	10,915
19	Christian	Pana	Lump	6	'04	S. W. P. '04	39.74	43.72	7.80	8.74	2.96	12,902
20	Clinton	Breese	Slack	6	'04	S. W. P. '04	43.66	34.00	8.10	14.24	3.40	12,181
21	Clinton	Breese	Nut	6	'04	S. W. P. '04	46.96	35.24	8.83	8.97	3.17	12,631
22	Clinton	Buxton	Lump	6	'04	S. W. P. '04	46.21	36.69	7.95	9.15	3.24	12,777
23	Clinton	Trenton	Nut	7	'04	S. W. P. '04	43.05	28.00	8.76	20.19	1.32	11,065
24	Clinton	Trenton	Slack	7	'04	S. W. P. '04	45.27	29.98	9.47	15.28	1.12	11,371
25	Coles	Paradise	Lump		Feb. 26 '97	Chem. Dept.	48.33	34.56	10.72	6.39	......	11,430
26	Crawford	Flatrock			Jan. 10 '05	Chem. Dept.	36.14	35.74	2.22	25.90	2.00	10,699
27	Franklin	Benton	Lump		May 4. '05	Chem. Dept.	51.12	36.23	3.04	9.61	2.62	12,983
28	Fulton	Astoria	Average		Jan. '98	B. L. S. '02	39.40	40.00	12.26	8.34	3.16	12,566
29	Fulton	Astoria	Lump	5	'04	S. W. P. '04	46.67	36.75	7.94	8.46	2.18	12,953
30	Fulton	Astoria	Slack	5	'04	S. W. P. '04	36.24	34.46	9.34	19.96	3.50	11,285
31	Fulton	Canton	Lump	5	'04	S. W. P. '04	38.56	35.98	11.10	14.36	3.67	12,217
32	Fulton	Canton	Nut	5	'04	S. W. P. '04	41.40	38.72	10.00	9.88	2.67	12,825
33	Fulton	Cuba			July '98	B. L. S. '02	40.96	36.93	10.42	11.69	4.60	12,056
34	Fulton	Cuba	Slack	5	'04	S. W. P. '04	43.34	39.19	7.70	9.77	3.10	13,035
35	Fulton	Cuba	Lump	5	'04	S. W. P. '04	41.38	38.26	9.23	11.14	1.50	12,622
36	Fulton	Cuba	Lump	5	'04	S. W. P. '04	43.26	41.01	5.55	10.18	2.22	12,905
37	Fulton	Cuba	Slack	5	'04	S. W. P. .04	40.71	36.33	7.28	15.68	3.35	11,988
38	Fulton	Dunfermline			June '98	B. L. S. '02	36.54	34.80	10.95	17.71	3.13	11,623
39	Fulton	Farmington			July '98	B. L. S. '02	36.50	35.93	11.12	16.25	3.98	11,847
40	Fulton	Farmington	Vein Sample		'78	B. L. S. '02	50.48	29.28	8.52	11.72	3.28	......
41	Fulton	Farmington	Lump	5	'04	S. W. P. '04	41.79	35.75	10.25	12.21	1.97	12,497
42	Fulton	Farmington	Slack	5	'04	S. W. P. '04	37.16	33.04	9.62	20.18	3.02	11,234
43	Fulton	Fiatt			July '98	B. L. S. '02	40.04	35.86	12.54	11.56	4.67	12,451

44	Fulton	Norris	Lump	5	'04	S. W. P. '04	40.84	33.20	11.78	14.18	1.93	11,767
45	Fulton	Norris	Slack	5	'04	S. W. P. '04	37.18	33.68	9.44	19.70	1.98	11,379
46	Fulton	St. David	Nut No. 2		Feb. 28, '06	Chem. Dept.	41.94	36.43	10.25	11.38	2.63	12,061
47	Fulton	St. David	Drill Core		May 12, '06	Chem. Dept.	50.96	40.21	3.08	5.75	3.23	13,941
48	Fulton	St. David	Drill Core		May 12, '06	Chem. Dept.	48.06	39.05	2.90	9.99	6.80	12,588
49	Gallatin	Junction	Pea		Mar. 20, '99	Chem. Dept.	43.52	37.04	9.11	10.33	3.65	......
50	Grundy	Braceville	Slack	2	'04	S. W. P. '04	32.24	26.88	9.70	31.18	3.55	9,574
51	Grundy	Braceville	Lump	2	'04	S. W. P. '04	46.80	37.32	11.86	4.02	2.18	13,797
52	Grundy	S. Wilmington	Slack	2	'04	S. W. P. '04	34.01	28.84	7.80	29.35	3.98	9,847
53	Grundy	S. Wilmington	Lump	2	'04	S. W. P. '04	46.11	37.09	11.44	5.36	2.10	13,531
54	Hamilton	Delafield	Drill Core		Jan. 31, '06	Chem. Dept.	48.01	38.46	.31	13.22	3.20	12,967
55	Hamilton	McLeansboro			July '05	Chem. Dept.	50.51	34.34	5.04	10.11	2.77	13,402
56	Hancock	Augusta			July '98	B. L. S. '02	41.32	44.37	10.78	3.53	2.48	13,164
57	Henry	Briar Bluff	Vein Sample		'78	B. L. S. '02	48.54	28.96	12.60	9.90	4.62	......
58	Henry	Galva			Oct. '98	B. L. S. '02	36.54	36.72	10.39	16.35	3.26	11,249
59	Henry	Kewanee	Vein Sample		'78	B. L. S. '02	49.66	27.60	15.60	7.14	2.22	......
60	Henry	Kewanee	Nut	6	'04	S. W. P. '04	45.87	37.33	10.16	6.64	2.50	12,560
61	Henry	Kewanee	Slack	6	'04	S. W. P. '04	44.99	37.99	9.99	7.03	2.57	12,523
62	Jackson	Carbondale	Vein Sample		'78	B. L. S. '02	59.88	26.40	6.32	7.40	.80	13,154
63	Jackson	Carbondale				B. L. S. '02	57.50	33.65	4.25	4.60	....	13,140
64	Jackson	Carbondale			May '96	B. L. S. '02	46.22	39.78	6.08	7.92	....	11,787
65	Jackson	Carbondale			May '96	B. L. S. '02	49.12	34.10	6.18	10.60	....	12,183
66	Jackson	De Soto	Mine Run		Nov. '99	B. L. S. '02	51.18	34.08	4.32	10.42	1.46	......
67	Jackson	De Soto	No. 1 W		Nov. '99	B. L. S. '02	52.04	34.63	5.27	8.06	1.73	......
68	Jackson	De Soto	No. 2 W		Nov. '99	B. L. S. '02	51.62	35.72	4.34	8.32	2.03	......
69	Jackson	De Soto	No. 3 W		Nov. '99	B. L. S. '02	49.40	36.76	4.32	9.52	1.70	......
70	Jackson	De Soto	No. 4 W		Nov. '99	B. L. S. '02	52.46	35.77	3.82	7.95	2.98	......
71	Jackson	De Soto	Refuse From Water		Nov. '99	B. L. S. '02	28.65	22.71	2.88	45.76	2.80	......
72	Jackson	Mt. Carbon	Vein Sample		'78	B. L. S. '02	66.58	24.68	6.12	2.70	.60	13,535
73	Jackson	Murphysboro	Lump		Mar. '00	B. L. S. '02	56.37	35.61	3.26	4.76	.76	......
74	Jackson	Murphysboro	Lump	1	'04	S. W. P. '04	56.03	34.62	4.96	4.39	.62	13,978
75	Jackson	Murphysboro	Lump	1	'04	S. W. P. '04	54.78	34.29	6.21	4.72	.62	13,955
76	Knox	Etherly	Lump	6	'04	S. W. P. '04	42.74	36.66	12.74	7.86	1.56	12,816
77	Knox	Etherly	Slack	6	'04	S. W. P. '04	33.65	31.19	10.16	25.00	2.48	10,218
78	Knox	Soperville	Drill Core		Feb. 21, '06	Chem. Dept.	46.46	42.51	5.17	5.86	2.97	12,915
79	La Salle	Kangley	Lump	7	'04	S. W. P. '04	41.88	38.94	7.68	8.50	3.24	13,258
80	La Salle	Kangley	Slack	7	'04	S. W. P. '04	38.54	33.05	5.81	22.60	4.96	11,137
81	La Salle	La Salle	Lump	2	'04	S. W. P. '04	42.06	45.30	7.54	5.10	3.04	13,476
82	La Salle	La Salle	Slack	2	'04	S. W. P. '04	39.02	38.91	7.87	14.20	3.35	11,821
83	La Salle	La Salle	Pea	2	'04	S. W. P. '04	42.58	41.78	7.56	8.08	3.92	13,016
84	La Salle	La Salle			'89	B. L. S. '02	43.95	39.40	8.22	8.43	....	13,259
85	La Salle	Oglesby	2nd Vein	2	'78	B. L. S. '02	49.32	30.84	12.12	7.72	2.02	......
86	La Salle	Oglesby	3rd Vein	3	'78	B. L. S. '02	55.88	30.34	10.06	3.72	2.27	......
87	La Salle	Oglesby	Egg	2	'04	S. W. P. '04	43.60	42.03	10.28	4.09	2.62	13,185
88	La Salle	Oglesby	Slack	2	'04	S. W. P. '04	38.26	35.92	8.28	17.54	4.66	11,253
89	La Salle	Peru			'89	B. L. S. '02	47.20	37.19	9.00	6.61	....	12,999
90	La Salle	Peru	Vein Sample	2, 3	'78	B. L. S. '02	51.26	33.90	10.30	4.54	3.05	......
91	La Salle	Streator	Slack	2	'04	S. W. P. '04	43.52	36.03	8.47	11.98	4.30	12,174
92	La Salle	Streator	Lump	2	'04	S. W. P. '04	45.85	39.84	7.96	6.35	3.38	13,597
93	La Salle	Streator	Slack	7	'04	S. W. P. '04	44.81	38.74	6.88	9.57	3.66	13,096
94	La Salle	Streator	Lump	7	'04	S. W. P. '04	46.98	42.10	5.52	5.40	3.07	13,824

TABLE VII (*Continued*)

No.	Source of Sample: County	Source of Sample: Town	Description: Size	Description: Geol. Seam	Date of Analysis	Analysis Obtained from	Proximate Analysis of Illinois Coal: Fixed Carbon	Volatile Matter	Moisture	Ash	Sulphur	B. T. U. per lb. of Total Dry Coal
95	Livingston	Cardiff	Lump	2	'01	S. W. P. '04	44.52	39.36	11.28	4.81	2.41	13,301
96	Livingston	Cardiff	Slack	2	'04	S. W. P. '01	41.18	36.54	10.26	12.02	2.96	12,053
97	Livingston	Fairbury	Slack	5	'01	S. W. P. '04	39.44	33.76	5.30	21.50	1.36	10,870
98	Livingston	Fairbury	Lump	5	'04	S. W. P. '04	43.67	39.07	6.57	10.69	2.20	12,999
99	Livingston	Forest	Drill Core	1	Oct. '98	B. L. S. '02	42.99	39.37	5.19	12.45	2.81	......
100	Livingston	Forest	Drill Core	2	Oct. '98	B. L. S. '02	40.04	44.83	4.36	10.77	3.76	......
101	Logan	Lincoln	....	......	....	B. L. S. '02	46.88	34.19	8.36	10.57	2.59	......
102	Logan	Lincoln	....	......	'89	B. L. S. '02	44.55	31.99	8.45	12.06	....	12,312
103	Logan	Lincoln	....	......	'89	B. L. S. '02	49.50	31.30	7.50	11.70	....	12,668
104	Logan	Lincoln	Vein Sample	......	'78	B. L. S. '02	46.61	27.60	10.92	14.81	4.99	......
105	Logan	Lincoln	Lump	5	'04	S. W. P. '04	37.58	36.78	10.61	15.00	3.17	12,161
106	Logan	Lincoln	Nut	5	'04	S. W. P. '01	42.10	38.88	10.44	8.58	2.44	12,247
107	Logan	Mt. Pulaski	Lump	5	'04	S. W. P. '04	42.28	33.61	11.98	12.10	2.73	12,308
108	Logan	Mt. Pulaski	....	......	....	B. L. S. '02	46.53	35.82	7.68	9.97	....	12,305
109	McDonough	Colchester	....	......	July '98	B. L. S. '02	40.09	34.07	9.04	16.80	1.16	11,653
110	McLean	Bloomington	Vein Sample	......	'78	B. L. S. '02	53.12	34.02	7.90	4.96	1.97	13,375
111	McLean	Bloomington	Lump	......	'96	B. L. S. '02	43.50	43.90	3.80	8.80	....	12,443
112	McLean	Bloomington	....	......	'89	B. L. S. '02	45.20	35.99	4.10	14.71	....	11,797
113	McLean	Bloomington	Slack	2	'04	S. W. P. '04	35.63	34.05	6.77	23.55	4.14	10,884
114	McLean	Bloomington	Lump	2	'04	S. W. P. '04	40.60	40.06	7.56	11.78	3.14	12,680
115	McLean	Bloomington	Slack	3	'01	S. W. P. '01	39.84	38.06	5.61	16.46	3.10	12,069
116	McLean	Bloomington	Lump	3	'04	S. W. P. '01	43.84	44.06	6.98	5.12	2.48	13,751
117	McLean	Colfax	Lump	......	May '02	Chem. Dept	42.58	41.35	8.02	8.05	1.80	12,025
118	Macon	Decatur	Lump	5	'04	S. W. P. '04	44.97	38.56	8.46	8.01	2.13	12,264
119	Macon	Niantic	Nut	5	'01	S. W. P. '01	44.01	36.47	10.38	9.14	3.27	12,056
120	Macon	Niantic	Slack	5	'04	S. W. P. '04	39.32	34.51	11.01	15.16	3.35	11,175
121	Macon	Niantic	Nut	......	Jan. 16 '95	B. L. S. '02	40.55	34.25	4.44	20.79	....	11,203
122	Macon	Niantic	....	......	'89	B. L. S. '02	47.80	36.25	7.88	8.47	....	12,515
123	Macon	Niantic	....	......	'89	B. L. S. '02	45.50	34.15	11.85	8.50	....	13,079
124	Macoupin	Brighton	Lump	......	Dec. 30, '04	Chem. Dept	49.51	35.43	7.87	7.16	2.68	13,230
125	Macoupin	Green Ridge	Lump	6	'04	S. W. P. '04	44.50	39.96	10.24	5.30	1.98	13,581
126	Macoupin	Green Ridge	Slack	6	'01	S. W. P. '04	37.50	32.98	8.38	21.14	3.00	10,990
127	Macoupin	Mt. Olive	Lump	6	'04	S. W. P. '04	43.78	42.39	9.30	4.53	3.80	13,066
128	Macoupin	Mt. Olive	Slack	6	'04	S. W. P. '01	41.62	34.21	9.62	14.55	3.86	11,433
139	Macoupin	Mt. Olive	....	......	'89	B. L. S. '02	41.49	36.13	7.97	11.11	....	12,432
130	Macoupin	Mt. Olive	....	......	'89	B. L. S. '02	51.50	35.00	5.30	8.20	....	12,431
131	Macoupin	Mt. Olive	....	......	Feb. '95	B. L. S. '02	44.51	38.59	7.99	8.91	....	......
132	Macoupin	Mt. Olive	Lump	......	May '01	B. L. S. '02	40.22	38.33	9.63	11.82	6.78	12,252
123	Macoupin	Palmyra	Drill Core	......	Feb. 9, '05	Chem. Dept	51.30	35.28	6.63	6.79	2.44	13,024
134	Macoupin	Palmyra	Drill Core	......	Feb. 9 '05	Chem. Dept	49.41	35.82	6.39	8.35	4.13	13,063
135	Macoupin	Palmyra	Drill Core	......	Feb. 9 '05	Chem. Dept	42.07	42.26	6.22	9.45	2.48	12,818
136	Macoupin	Virden	Nut	6	'01	S. W. P. '04	43.40	38.25	10.27	8.08	1.50	12,826
137	Macoupin	Virden	Slack	6	'04	S. W. P. '04	42.32	37.60	10.21	9.87	2.80	12,184

138	Madison	Collinsville	Nut	6	'04	S. W. P. '04	42.34	38.31	8.26	11.06	3.09	12,802
139	Madison	Collinsville	Pea	6	'04	S. W. P. '04	38.67	35.91	7.71	17.68	4.08	11,440
140	Madison	Donkville	W. Nut	6	'04	S. W. P. '04	44.66	39.86	8.08	7.40	3.00	13,059
141	Madison	Donkville	W. Pea	6	'01	S. W. P. '01	45.53	40.83	4.87	8.77	2.96	12,997
142	Madison	Edwardsville	Nut	6	'01	S. W. P. '01	40.91	36.93	7.76	14.40	4.74	11,928
143	Madison	Edwardsville	Slack	6	'01	S. W. P. '01	39.33	36.37	8.54	15.76	4.00	11,895
144	Madison	Glen Carbon	Lump	....	May '01	B. L. S. '02	40.66	39.13	7.85	12.36	4.87	12,522
145	Marion	Centralia	....	......	'89	B. L. S. '02	45.50	38.18	8.28	8.04	....	......
146	Marion	Centralia	Duff	......	....	B. L. S. '02	36.00	36.10	1.50	26.40	4.01	......
147	Marion	Centralia	Slack	6	'04	S. W. P. '01	40.76	31.13	6.75	18.36	4.36	11,620
148	Marion	Centralia	Nut	6	'04	S. W. P. '04	43.99	38.17	5.43	12.41	3.60	12,327
149	Marion	Kinmundy	....	......	'97	B. L. S. '02	42.78	33.63	6.15	17.44	7.25	......
150	Marion	Kinmundy	....	......	....	B. L. S. '02	47.45	34.00	7.00	11.15	....	12,542
151	Marion	Odin	Lump	......	Jan. '95	B. L. S. '02	46.02	40.25	6.20	7.53	....	12,665
152	Marion	Odin	Lump	......	Feb. '95	B. L. S. '02	44.45	37.73	6.32	11.50	....	......
153	Marion	Odin	Lump	......	Apr. '95	B. L. S. '02	48.09	34.90	7.10	9.91	....	12,110
154	Marion	Odin	Pea	......	July '96	B. L. S. '02	42.30	37.93	5.09	14.68	....	11,569
155	Marion	Odin	Pea	......	Oct. '96	B. L. S. '02	45.23	41.25	7.28	6.24	....	12,619
156	Marion	Odin	Lump	......	Nov. '96	B. L. S. '02	45.77	40.76	7.21	6.23	....	11,195
157	Marion	Odin	Lump	......	Nov. '96	B. L. S. '02	45.57	38.39	7.92	8.12	....	13,293
158	Marion	Odin	Lump	......	Nov. '96	B. L. S. '02	44.62	35.73	8.11	11.54	....	12,537
159	Marion	Odin	Slack	......	Dec. '96	B. L. S. '02	42.26	31.31	8.00	15.43	....	12,609
160	Marion	Odin	Lump	......	Jan. '97	B. L. S. '02	47.35	38.30	3.50	10.85	....	12,777
161	Marion	Odin	Pea	......	Jan. '97	B. L. S. '02	44.23	36.22	4.20	15.35	....	12,307
162	Marion	Odin	Lump	......	Feb. '97	B. L. S. '02	41.85	34.07	8.12	15.70	....	12,874
163	Marion	Odin	Lump	......	Feb. '97	B. L. S. '02	44.15	36.10	8.55	11.20	....	12,597
164	Marion	Odin	Pea	......	Mar. '97	B. L. S. '02	42.44	35.43	7.71	14.42	....	12,482
165	Marion	Odin	Pea	......	Mar. '98	B. L. S. '02	42.23	38.17	7.25	11.35	3.61	11,711
166	Marion	Odin	....	......	Mar. '95	B. L. S. '02	44.45	37.73	6.32	11.50	....	11,681
167	Marion	Odin	Pea	......	Mar. '97	B. L. S. '02	39.54	31.95	6.48	22.03	....	......
168	Marion	Odin	Pea	......	Mar. '99	B. L. S. '02	46.70	34.65	6.70	11.95	3.43	......
169	Marion	Odin	Pea	......	'99	B. L. S. '02	46.05	33.78	4.70	15.47	4.80	......
170	Marion	Odin	....	......	'89	B. L. S. '02	50.86	33.99	6.07	9.08	....	12,726
171	Marion	Odin	Lump	......	Feb. '96	B. L. S. '02	47.22	36.46	9.10	7.22	....	12,574
172	Marion	Odin	....	......	'89	B. L. S. '02	46.90	41.10	5.90	6.10	....	13,457
173	Marion	Odin	Pea	......	'97	B. L. S. '02	39.51	31.95	6.48	22.03	4.31	......
174	Marion	Odin	Lump	......	'97	B. L. S. '02	44.23	37.05	6.81	11.91	2.68	......
175	Marion	Odin	Pea	......	May '00	B. L. S. '02	42.96	35.76	7.27	14.01	3.88	12,072
176	Marion	Odin	Nut	6	'04	S. W. P. '04	44.55	37.11	8.52	9.82	3.00	12,175
177	Marion	Odin	Slack	6	'04	S. W. P. '04	40.97	36.16	6.92	15.95	3.80	11,566
178	Marion	Odin	Duff	......	Mar. 28, '05	Chem. Dept	45.14	31.79	7.21	15.86	2.12	11,185
179	Marion	Sandoval	Vein Sample	......	Oct. 30, '05	Chem. Dept	45.89	36.41	5.03	12.67	8.05	12,249
180	Marion	Sandoval	Lump	6	'04	S. W. P. '04	45.74	36.81	5.51	11.94	2.60	12,721
181	Marion	Sandoval	....	......	'89	B. L. S. '02	50.86	35.07	7.19	6.88	....	12,885
182	Marshall	Toluca	....	......	July '98	B. L. S. '02	41.32	33.07	8.95	16.66	4.64	11,861
183	Marshall	Wenona	Lump	2	'01	S. W. P. '01	50.15	36.59	10.91	2.32	.79	13,630
184	Marshall	Wenona	Slack	2	'01	S. W. P. '01	43.06	33.49	10.31	13.14	2.67	12,230
185	Menard	Athens	Lump	5	'04	S. W. P. '04	42.32	39.32	9.32	9.04	4.44	12,685
186	Menard	Athens	Slack	5	'01	S. W. P. '01	38.46	34.82	10.10	16.62	4.20	11,114
187	Menard	Athens	....	......	'97	B. L. S. '02	43.60	35.57	10.01	10.82	2.40	......
188	Menard	Athens	....	......	Mar. '97	B. L. S. '02	41.95	35.18	12.11	10.76	....	13,821
189	Menard	Greenview	....	......	July '00	B. L. S. '02	41.21	39.20	10.91	8.65	3.15	12,443

TABLE VII (*Continued*)

No.	Source of Sample		Description		Date of Analysis	Analysis Obtained from	Proximate Analysis—Air-Dry Coal					B. T. U. per lb. of Total Dry Coal
	County	Town	Size	Geol. Seam			Fixed Carbon	Volatile Matter	Moisture	Ash	Sulphur	
190	Menard	Greenview	Lump	5	'04	S. W. P., '04	44.81	37.62	9.46	8.11	2.41	12,757
191	Menard	Greenview	Slack	5	'04	S. W. P., '04	39.88	36.28	9.58	14.26	3.04	11,863
192	Menard	Middletown	Lump	5	'04	S. W. P., '04	43.17	36.89	10.04	9.90	2.43	12,550
193	Menard	Middletown	Slack	5	'04	S. W. P., '04	37.31	33.12	10.37	19.20	3.13	10,933
194	Menard	Petersburg	Slack	......	Dec. 17, '01	Chem. Dept.	39.54	33.32	4.69	22.45	5.68	10,806
195	Menard	Petersburg	Lump	......	Dec. 17, '04	Chem. Dept.	50.89	35.04	6.30	7.77	2.46	13,027
196	Mercer	Cable	Lump	1	'04	S. W. P., '04	40.78	39.34	9.02	10.86	3.93	12,588
197	Mercer	Cable	Slack	1	'04	S. W. P., '04	41.43	37.77	9.02	11.78	4.00	12,508
198	Mercer	Gilchrist	......	......	July, '98	B. L. S., '02	35.32	36.94	7.48	20.26	4.86	11,479
199	Mercer	Sherrard	Lump	1	'01	S. W. P., '01	42.22	39.36	9.60	8.82	3.02	13,136
200	Mercer	Sherrard	Slack	1	'01	S. W. P., '04	37.05	36.72	7.84	18.39	4.78	11,004
201	Montgomery	Litchfield	Slack	2	'01	S. W. P., '04	41.88	36.34	7.94	13.84	3.10	12,104
202	Montgomery	Litchfield	Lump	2	'04	S. W. P., '01	46.08	38.74	9.22	5.96	1.77	13,329
203	Peoria	Elmwood	......	......	July, '98	B. L. S., '02	40.76	44.45	9.38	5.41	2.61	13,606
204	Peoria	Elmwood	Vein Sample	3	July, '98	B. L. S., '02	41.30	43.63	8.70	6.37	2.75	13,603
205	Peoria	Elmwood	Vein Sample	5	July, '98	B. L. S., '02	42.30	26.78	10.55	10.37	1.29	12,879
206	Peoria	Elmwood	Vein Sample	6	July, '98	B. L. S., '02	43.90	35.50	9.30	11.30	3.16	12,403
207	Peoria	Elmwood	Vein Sample	......	'78	B. L. S., '02	55.30	27.60	7.60	9.50	2.18	......
208	Peoria	Holles	Lump	2	'01	S. W. P., '04	41.80	42.66	7.86	7.68	2.41	12,893
209	Peoria	Holles	Nut	2	'01	S. W. P., '01	43.03	41.13	8.04	7.80	3.13	12,956
210	Perry	Du Quoin	Lump	......	June 16, '98	Chem. Dept.	48.59	33.15	8.13	9.21	....	......
211	Perry	Du Quoin	......	......	'97	B. L. S. '02	49.51	33.15	8.13	9.21	.83	......
212	Perry	Du Quoin	Vein Sample	......	'78	B. L. S. '02	60.60	23.54	8.86	7.00	1.88	12,355
213	Perry	Du Quoin	......	......	......	B. L. S. '02	41.60	35.03	7.03	13.31	....	11,820
214	Perry	Du Quoin	......	......	......	B. L. S. '02	53.69	32.03	6.84	7.44	....	13,064
215	Perry	Du Quoin	......	......	......	B. L. S. '02	54.08	30.35	6.67	8.90	....	13,279
216	Perry	Du Quoin	Lump	......	Feb. '95	B. L. S. '02	45.10	39.81	7.43	7.66	....	......
217	Perry	Du Quoin	Lump	......	Sept. '95	B. L. S. '02	47.53	35.77	7.59	9.11	....	12,174
218	Perry	Du Quoin	Lump	......	June '96	B. L. S. '02	50.85	34.61	9.14	5.40	....	13,273
219	Perry	Du Quoin	Slack	......	May '98	B. L. S. '02	41.60	35.95	6.05	16.40	5.14	11,762
220	Perry	Du Quoin	......	......	Jan. '95	B. L. S. '02	44.56	35.03	7.02	13.39	....	11,819
221	Perry	Du Quoin	Nut	6	'01	S. W. P. '01	49.07	35.97	8.44	6.52	1.82	13,055
222	Perry	Du Quoin	Nut	6	'01	S. W. P. '04	44.00	38.72	7.24	10.04	3.01	12,710
223	Perry	DuQuoin	Lump	......	Mar. 27, '06	Chem. Dept.	48.45	34.28	7.15	10.12	.71	12,218
224	Perry	Muddy Valley	Lump	......	July '96	B. L. S. '02	48.23	40.37	7.11	4.29	....	12,790
225	Perry	Pinckneyville	Lump	6	'01	S. W. P. '04	45.96	39.20	7.54	7.30	1.88	13,067
226	Perry	Pinckneyville	Slack	6	'01	S. W. P. '01	39.16	31.36	7.26	22.22	3.10	10,784
227	Perry	St. John	Lump	......	July '96	B. L. S. '02	51.10	37.00	9.63	2.27	....	13,245
228	Perry	St. John	Lump	......	Feb. '97	B. L. S. '02	48.34	34.56	10.72	6.38	....	13,104
229	Randolph	Sparta	Lump	6	'04	S. W. P. '04	46.28	37.61	7.44	8.64	2.40	12,738
230	Randolph	Sparta	Nut	6	'04	S. W. P. '01	47.23	36.75	7.09	8.93	3.45	12,744
231	Randolph	Tilden	Slack	6	'04	S. W. P. '04	44.98	34.70	7.17	13.15	3.13	12,313

232	Randolph	Tilden	Lump	6	'04	S. W. P. '04	46.53	37.06	8.68	7.73	3.07	12,620
233	St. Clair	French Village	Lump	6	'04	S. W. P. '04	42.21	41.30	8.08	8.38	3.35	12,564
234	St. Clair	French Village	Slack	6	'04	S. W. P. '04	40.23	35.41	8.12	16.21	4.00	11,443
235	St. Clair	Marissa	Lump	6	'04	S. W. P. '04	44.10	40.78	7.78	7.31	3.23	12,670
236	St. Clair	Marissa	Slack	6	'01	S. W. P. '01	41.21	37.87	7.15	13.77	3.93	11,760
237	St. Clair	Marissa	Nut		Feb. 22..'05	Chem. Dept.	48.45	33.35	3.92	14.28	3.00	12,074
238	St. Clair	Marissa	Lump		Apr. 1...'05	Chem. Dept.	56.79	31.90	5.67	5.61	1.53	13,305
239	Saline	Eldorado	Lump	5	'04	S. W. P. '04	52.10	33.32	5.68	8.90	1.18	13,431
240	Saline	Eldorado	Slack	5	'04	S. W. P. '01	42.70	29.36	4.36	23.58	2.00	10,874
241	Saline	Eldorado	Lump	7	'04	S. W. P. '01	49.72	34.36	5.04	10.88	4.00	12,825
242	Saline	Eldorado	Slack	7	'04	S. W. P. '01	41.31	30.78	4.00	20.88	3.70	11,379
243	Saline	Eldorado	Lump		Apr. ....'04	Chem. Dept.	55.27	34.75	2.31	7.67	.53	12,978
244	Saline	Galatia			July....'05	Chem. Dept.	48.73	33.91	5.44	11.92	2.96	13,009
245	Saline	Harrisburg	Lump		Apr. 26..'05	Chem. Dept.	56.39	31.12	6.01	6.48	.48	13,603
246	Saline	Harrisburg	Lump		Apr. 1....'05	Chem. Dept.	56.29	34.06	4.29	5.36	1.15	14,113
247	Saline	Harrisburg	Lump	5	'04	S. W. P. '04	53.18	37.12	4.20	5.50	1.61	13,886
248	Saline	Harrisburg	Lump	5	'04	S. W. P. '04	53.12	36.11	3.76	7.01	1.81	13,665
249	Saline	Harrisburg	Slack	5	'04	S. W. P. '04	47.36	33.14	3.70	15.80	2.40	10,993
250	Saline	Harrisburg	Lump	5	'01	S. W. P. '04	51.97	37.17	4.40	6.76	1.55	13,503
251	Saline	Harrisburg	Slack	5	'04	S. W. P. '04	48.28	32.72	4.72	14.28	2.70	11,913
252	Sangamon	Auburn	Lump	6	'04	S. W. P. '04	42.91	38.96	10.46	7.67	2.60	13,022
253	Sangamon	Auburn	Slack	6	'01	S. W. P. '04	39.75	31.50	9.38	16.37	3.50	11,602
254	Sangamon	Auburn	Nut	6	.04	S. W. P. '04	43.60	39.52	6.46	10.42	2.73	12,228
255	Sangamon	Auburn	Slack	6	.04	S. W. P. '04	40.00	35.78	10.10	14.12	3.02	11,831
256	Sangamon	Barclay				B. L. S. '02	46.20	35.70	7.40	10.70	....	12,100
257	Sangamon	Barclay	Vein Sample		'78	B. L. S. '02	45.60	27.32	10.08	17.00	3.21	......
258	Sangamon	Barclay	Pea		Apr.......'98	Chem. Dept.	45.19	38.15	3.76	12.90	....	......
259	Sangamon	Cantrall	Nut	5	'01	S. W. P. '04	43.45	38.31	10.02	8.22	1.54	12,821
260	Sangamon	Cantrall	Slack	5	'04	S. W. P. '01	40.78	36.91	9.64	12.61	3.45	12,095
261	Sangamon	Dawson	Nut	5	'01	S. W. P. '04	43.41	34.10	12.56	9.93	2.11	12,699
262	Sangamon	Dawson	Slack	5	'01	S. W. P. '04	42.44	29.18	11.44	16.91	3.13	11,319
263	Sangamon	Dawson	Pea		Mar. 4,...'99	B. L. S. '02	41.40	33.65	12.54	12.41	5.09	....
264	Sangamon	Dawson	Pea		'99	B. L. S. '02	43.17	35.25	9.38	12.20	2.83	......
265	Sangamon	Divernon	Lump		May......'01	B. L. S. '02	38.59	34.72	8.69	18.00	6.03	11,239
266	Sangamon	Lowder	Slack		Apr.......'04	Chem. Dept.	45.02	35.00	6.92	12.55	1.73	11,700
267	Sangamon	Ridgely			Feb.......'99	B. L. S. '02	41.14	36.94	9.41	12.21	4.09	......
268	Sangamon	Ridgely	Pea		Mar.......'99	B. L. S. '02	40.01	37.33	9.80	12.83	4.19	......
269	Sangamon	Riverton			'89	B. L. S. '02	48.45	35.39	6.38	9.78	....	12,426
270	Sangamon	Riverton			'89	B. L. S. '02	44.30	38.45	11.10	6.15	....	13,606
271	Sangamon	Riverton	Pea		Mar.......'99	B. L. S. '02	40.56	36.51	8.83	14.10	4.22	......
272	Sangamon	Riverton	Slack	5	'01	S. W. P. '04	43.20	36.96	3.38	16.46	4.10	11,818
273	Sangamon	Riverton	Pea		Jan.......'04	Chem. Dept.	33.98	36.27	8.23	21.52	....	10,870
274	Sangamon	Riverton	Pea		Dec.......'03	Chem. Dept.	43.20	36.96	3.38	16.46	1.01	11,542
275	Sangamon	Spaulding	Lump		Feb.......'97	B. L. S. '02	40.57	35.44	12.47	11.52	....	12,514
276	Sangamon	Springfield			'97	B. L. S. '02	41.68	35.89	10.15	11.98	2.99	......
277	Sangamon	Springfield	Lump	5	'01	S. W. P. '04	47.28	36.61	4.74	11.34	2.90	12,571
278	Sangamon	Springfield	Lump	5	'04	S. W. P. '04	38.64	37.08	11.32	12.96	3.90	12,032
279	Sangamon	Springfield	Slack	5	'04	S. W. P. '01	41.74	31.51	11.56	12.16	4.08	12,217
280	Sangamon	Springfield	Pea		Nov.......'05	Chem. Dept.	42.41	36.59	5.42	15.55	6.14	12,591
281	Sangamon	Springfield			Sep. 23...'05	Chem. Dept.	44.52	35.15	8.55	11.78	3.55	12,364
282	Sangamon	Springfield	Lump		Feb. 2...'00	Chem. Dept.	34.35	32.33	.99	32.32	1.07	11,098
283	Sangamon	Springfield	Pea		Apr. 27...'06	Chem. Dept.	41.12	34.26	10.95	13.67	2.90	11,939

TABLE VII (*Concluded*)

No.	Source of Sample		Description		Date of Analysis	Analysis Obtained from	Proximate Analysis—Air-Dry Coal					B. T. U. per lb. of Total Dry Coal
	County	Town	Size	Geol. Seam			Fixed Carbon	Volatile Matter	Moisture	Ash	Sulphur	
284	Sangamon	Springfield Jc.			Feb. '99	B. L. S. '02	43.52	37.04	9.11	10.33	3.65	......
285	Sangamon		Lump		Feb. '97	Chem. Dept.	40.57	35.41	12.47	11.52	....	11,980
286	Sangamon				Apr '04	Chem. Dept.	43.52	37.04	9.11	10.33	3.65	11,930
287	Sangamon				Jan. '05	Chem. Dept.	41.57	36.56	8.79	13.08	3.42	12,162
288	Sangamon				Apr. '05	Chem. Dept.	41.33	32.28	9.19	17.20	3.76	11,537
289	Shelby	Moweaqua	Lump		Jan. '95	B. L. S. '02	43.75	39.58	9.18	7.49	....	13,026
290	Shelby	Moweaqua	Lump	1	Dec. '95	B. L. S. '02	45.57	36.57	8.77	9.09	....	......
291	Shelby	Moweaqua	Lump	2	Dec. '95	B. L. S. '02	42.14	42.80	7.08	7.98	....	......
292	Shelby	Moweaqua	Lump	5	Dec. '95	B. L. S. '02	46.00	39.53	8.00	6.47	....	......
293	Shelby	Moweaqua				B. L. S. '02	42.09	37.00	7.17	13.74	....	11,185
294	Shelby	Moweaqua	Nut	5	'04	S. W. P '01	41.01	37.14	8.07	10.78	3.30	12,157
295	Shelby	Moweaqua	Slack	5	'04	S. W. P. '04	43.83	36.82	9.19	10.16	3.27	12,401
296	Vermilion	Catlin	Lump	7	'04	S. W. P. '04	45.75	38.18	10.36	5.71	1.47	13,203
297	Vermilion	Catlin	Slack	7	'04	S. W. P. '04	44.33	40.75	9.90	5.02	2.00	11,487
298	Vermilion	Catlin	Vein Sample		'78	B. L. S. '02	48.42	31.08	7.80	12.70	3.96	......
299	Vermilion	Catlin	Screen		Mar. '05	Chem. Dept.	43.40	29.62	7.41	19.57	2.12	12,369
300	Vermilion	Danville	Vein Sample		'78	B. L. S. '02	44.56	31.20	9.60	14.64	2.72	......
301	Vermilion	Danville				B. L. S. '02	45.37	43.70	4.78	6.15	....	13,134
302	Vermilion	Danville				B. L. S. '02	46.42	37.07	5.62	10.88	....	12,349
303	Vermilion	Danville				B. L. S. '02	53.00	32.35	11.00	3.65	....	13,803
304	Vermilion	Danville	Screen		May '96	B. L. S. '02	31.20	33.30	9.40	23.10	....	10,331
305	Vermilion	Danville	Lump		Mar. '00	B. L. S. '02	40.50	47.47	7.56	4.47	3.62	......
306	Vermilion	Danville	Lump		Mar. '00	B. L. S. '02	47.37	40.64	8.06	3.93	1.27	......
307	Vermilion	Danville	Slack	7	'04	S. W. P. '04	48.14	35.06	3.41	13.36	3.38	12,333
308	Vermilion	Danville	Lump	7	'04	S. W. P. '04	43.01	45.96	8.38	5.65	2.88	13,740
309	Vermilion	Danville	Slack	7	'04	S. W. P. '04	37.70	34.83	8.00	19.47	3.40	11,525
310	Vermilion	Danville	Lump	6	'04	S. W. P. '04	41.80	41.81	9.30	7.06	2.40	12,552
311	Vermilion	Fairmount	Slack	7	'04	S. W. P '04	37.25	36.47	7.59	18.69	3.67	11,134
312	Vermilion	Fairmount	Screen		Dec. '96	B. L. S. '02	39.85	36.46	10.67	13.02	....	12,191
313	Vermilion	Fairmount	Screen			B. L. S. '02	47.05	31.80	8.10	13.05	....	12,438
314	Vermilion	Grape Creek	Vein Sample		July '78	B. L. S. '02	51.32	28.34	9.74	10.60	3.63	......
315	Vermilion	Grape Creek	Lump	6	'04	S. W. P. '04	46.76	35.49	11.85	5.90	2.43	13,120
316	Vermilion	Grape Creek	Lump	6	'04	S. W. P. '01	48.48	34.81	11.57	5.14	.75	13,186
317	Vermilion	Oakwood			'89	B. L. S. '02	46.00	37.55	7.80	8.65	....	13,587
318	Vermilion	Oakwood	Lump		Mar. '05	Chem. Dept.	45.13	37.40	6.80	10.67	3.40	12,503
319	Vermilion	Oakwood	Screen		Apr. '05	Chem. Dept.	42.19	35.55	8.21	14.02	3.23	11,427
320	Vermilion	Oakwook	Screen		Apr. '05	Chem. Dept.	38.88	33.43	6.02	21.67	3.21	10,299
321	Vermilion	Oakwood	Screen		May. '05	Chem. Dept.	41.76	35.25	6.08	16.91	3.14	11,067
322	Vermilion	Oakwood	Pea		Nov. 25, '05	Chem. Dept.	41.47	39.85	5.62	13.06	3.63	13,251
323	Vermilion	Westville	Mine Run		Mar. 12, '00	Chem. Dept.	48.19	39.86	8.02	3.94	1.27	14,384
324	Vermilion	S. Westville	Lump	6	'04	S. W. P. '04	47.12	35.86	11.20	5.82	.83	13,315
325	Vermilion	S. Westville	Slack	6	'04	S. W. P. '04	46.30	35.34	11.06	7.30	.84	13,078

326	Wabash	Sugar Creek	Hand Sample	....	Jan. ..... '01	B. L. S. '02	48.79	41.30	6.03	3.88	1.73	.....
327	Will	Braidwood	Lump	2	.... '04	S. W. P. '01	48.02	36.28	11.44	4.26	1.95	12,760
328	Will	Braidwood	Slack	2	.... '04	S. W. P. '04	40.53	32.57	10.52	16.38	2.31	10,812
329	Will	Joliet	No. 1	....	Sept. .... '05	Chem. Dept.	45.55	38.05	11.98	4.42	2.21	13,866
330	Will	Joliet	No. 2	....	Sept. .... '05	Chem. Dept.	48.94	36.57	10.35	4.14	2.01	14,014
331	Will	Joliet	No. 3	....	Sept. .... '05	Chem. Dept.	47.94	36.26	11.52	4.28	2.43	13,844
332	Williamson	Bush	Lump	7	.... '01	S. W. P. '04	49.11	35.00	5.90	9.96	1.97	12,829
333	Williamson	Bush	Slack	7	.... '01	S. W. P. '04	47.20	35.64	1.92	12.21	1.15	12,477
334	Williamson	Carterville	Slack	7	.... '04	S. W. P. '04	53.16	33.18	6.04	7.62	1.03	13,422
335	Williamson	Carterville	Lump	7	.... '04	S. W. P. '04	54.99	32.58	6.32	6.10	1.00	13,563
336	Williamson	Carterville	W. Nut	7	.... '04	S. W. P. '04	56.20	32.00	3.28	8.52	.89	12,986
337	Williamson	Carterville	Mine Run	....	May. .... '00	B. L. S. '02	52.17	34.11	4.87	8.85	.85	12,839
338	Williamson	Carterville	W. No. 1	....	May. .... '00	B. L. S. '02	54.21	33.99	4.66	7.14	.74	12,886
339	Williamson	Carterville	W. No. 2	....	May. .... '00	B. L. S. '02	55.01	35.12	4.31	5.56	.86	13,517
340	Williamson	Carterville	W. No. 4	....	May. .... '00	B. L. S. '02	55.29	33.26	4.86	6.59	1.15	12,976
341	Williamson	Carterville	W. No. 2	....	Mar. .... '29	B. L. S. '02	57.32	30.25	5.76	6.67	1.18	13,179
342	Williamson	Carterville	W. No. 2	....	Mar. .... '29	B. L. S. '02	52.34	34.20	7.35	6.11	1.05	12,716
343	Williamson	Carterville	W. Nut No. 2	....	May. 26, '05	Chem. Dept.	49.98	35.15	5.00	9.87	2.10	13,352
344	Williamson	Carterville	W. Nut No. 2	....	Dec. 19, '05	Chem. Dept.	56.30	32.00	3.28	8.52	.89	12,986
345	Williamson	Carterville	W. Pea Duff	....	Nov. ..... '05	Chem. Dept.	55.52	32.10	3.83	8.76	1.97	13,408
346	Williamson	Herrin	N. Ky. Pea	....	Apr. ..... '04	Chem. Dept.	53.32	33.10	2.94	10.64	1.42	12,769
347	Williamson	Herrin	N. Ky. W. Scr	....	Feb. ..... '04	Chem. Dept.	53.26	31.12	5.00	10.62	......	12,364
348	Williamson	Herrin	W. Slack	7	.... '04	S. W. P. '04	52.62	31.76	5.00	10.62	2.22	12,974
349	Williamson	Herrin	W. Nut	7	.... '04	S. W. P. '04	54.24	33.53	5.87	6.36	.83	13,498
350	Williamson	Herrin	W. Slack	7	.... '04	S. W. P. '04	52.41	30.96	5.16	11.17	1.85	12,846
351	Williamson	Herrin	Lump	7	.... '04	S. W. P. '04	56.22	32.32	6.00	5.46	.82	13,590
352	Williamson	Herrin	Vein Sample	....	Oct. ...... '00	B. L. S. '02	51.49	34.66	4.22	9.63	2.78	12,508
353	Williamson	Lake Creek	....	....	Mar. ...... '98	B. L. S. '02	53.20	39.30	3.42	4.08	1.72	12,673
354	Williamson	Lauder	Slack	7	.... '04	S. W. P. '04	35.04	40.81	6.35	17.80	1.14	11,221
355	Williamson	Sunnyside	W. No. 2	....	Jan. ..... '02	B. L. S. '02	55.28	33.86	3.97	6.89	......	13,004

TABLE VIII

List of Illinois Coals Analyzed. Arranged by Towns

Town	County	Ref. Number in Table of Analyses
Assumption	Christian	8-12
Astoria	Fulton	28-30
Athens	Menard	185-188
Auburn	Sangamon	252-255
Barclay	Sangamon	256-258
Benton	Franklin	27
Bloomington	McLean	110-116
Braceville	Grundy	50-51
Braidwood	Will	327-328
Breese	Clinton	20-21
Briar Bluff	Henry	57
Brighton	Macoupin	124
Bush	Williamson	332
Buxton	Clinton	22
Cable	Mercer	196-197
Canton	Fulton	31-32
Cantrall	Sangamon	259-260
Carbondale	Jackson	62-65
Cardiff	Livingston	95-96
Carterville	Williamson	333-345
Catlin	Vermilion	296-299
Centralia	Marion	145-148
Colchester	McDonough	109
Colfax	McLean	117
Collinsville	Madison	138-139
Cuba	Fulton	33-36
Danville	Vermilion	300-310
Dawson	Sangamon	261-264
Decatur	Macon	118
Delafield	Hamilton	54
De Soto	Jackson	66-71
Divernon	Sangamon	265
Donkville	Madison	140-141
Dunfermline	Fulton	38
Du Quoin	Perry	210-223
Edwardsville	Madison	142-143
Eldorado	Saline	239-243
Elm Grove	Adams	1-2
Elmwood	Peoria	203-207
Etherly	Knox	76-77
Fairbury	Livingston	97-98
Fairmount	Vermilion	311-313
Farmington	Fulton	39-42
Fiatt	Fulton	43
Flatrock	Crawford	26
Forest	Livingston	99-100
French Village	St. Clair	233-234
Galatia	Saline	244
Galva	Henry	58
Gilchrist	Mercer	198
Glen Carbon	Madison	144
Grape Creek	Vermilion	314-316
Greenview	Menard	189-191
Greenridge	Macoupin	125-126
Harrisburg	Saline	245-251
Herrin	Williamson	346-352
Holles	Peoria	208-209
Ivesdale	Champaign	7
Joliet	Will	329-331
Junction	Gallatin	49
Kangley	La Salle	79-80
Kewanee	Henry	59-61
Kinmundy	Marion	149-150
Ladd	Bureau	3-4
Lake Creek	Williamson	353

TABLE VIII (*Concluded*)

Town	County	Ref. Number in Table of Analyses
La Salle	La Salle	81-84
Lauder	Williamson	354
Lincoln	Logan	101-106
Litchfield	Montgomery	201-202
Lombardville	Bureau	5
Lowder	Sangamon	266
McLeansboro	Hamilton	55
Marissa	St. Clair	235-238
Middletown	Menard	192-193
Moweaqua	Shelby	289-295
Mt. Carbon	Jackson	72
Mt. Olive	Macoupin	127-132
Mt. Pulaski	Logan	107-108
Muddy Valley	Perry	224
Murphysboro	Jackson	73-75
Niantic	Macon	119-123
Norris	Fulton	44-45
Oakwood	Vermilion	317-322
Odin	Marion	151-178
Oglesby	La Salle	85-88
Palmyra	Macoupin	133-135
Pana	Christian	13-19
Paradise	Coles	25
Peru	La Salle	89-90
Petersburg	Menard	194-195
Pinckneyville	Perry	225-226
Ridgely	Sangamon	267-268
Riverton	Sangamon	269-274
St. David	Fulton	46-48
St. John	Perry	227-228
Sandoval	Marion	179-181
Sherrard	Mercer	199-200
Soperville	Knox	78
Sparta	Randolph	229-230
Spaulding	Sangamon	275
Springfield	Sangamon	276-283
Springfield Junction	Sangamon	284
Spring Valley	Bureau	6
Streator	La Salle	91-94
Sugar Creek	Wabash	326
Sunnyside	Williamson	355
Tilden	Randolph	231-232
Toluca	Marshall	182
Trenton	Clinton	23-24
Virden	Macoupin	136-137
Wenona	Marshall	183-184
Westville	Vermilion	323
S. Westville	Vermilion	324-325
S. Wilmington	Grundy	52-53

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

Bulletin No. 1. Tests of Reinforced Concrete Beams, by A. N. Talbot. 1904.

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by A. N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by A. P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by R. I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge. 1906.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 8 SEPTEMBER 1906

TESTS OF CONCRETE: I. SHEAR; II. BOND.

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS.

I. SHEAR.

Reference to current engineering literature and discussions will show that there exists in the minds of engineers quite diverse notions of the shearing resistance of concrete. Values as low as the tensile strength of the concrete are cited; others name a shearing resistance nearly as great as the compressive strength of the concrete. It seems evident that these divergent estimates must be due to inconsistent experimental methods or to improper conceptions of the nature of shearing action.

Shear is defined to be the action of two equal and oppositely directed forces whose lines of action are in planes very close together. Manifestly, in the actual application of forces to structures or even to test pieces, the applied forces are not in adjacent planes, and the shearing forces used in the analysis and calculation are forces which exist by virtue of the mechanics of the problem. The shearing stresses in concrete test pieces are discussed on the basis of some distribution throughout the section, generally a uniform or nearly uniform distribution. The importance of determining this distribution is not usually recognized. Shear should be differentiated from cutting action, in that the latter begins at the surface and involves, in some degree at least, a gradual tearing or detrusive action and a concentration of the

force at a single point. Shear should also be distinguished from the phenomena which may accompany it, as bearing action, diagonal tension, etc. In fact, the difficulties surrounding the determination of the shearing resistance of concrete are due largely to the accompanying cutting action, bearing pressures, and beam stresses involved in the test. In the breaking of reinforced concrete beams, shearing failures have been confused with diagonal tension failures (see Bulletin No. 4, p. 25), and calculations made from the results of such beam tests are evidently a source of low values given in texts and in the building ordinances of many of the cities of the country.

Fig. 1 illustrates a common conception of shear. The shearing force is considered to act along the line AB, and the shearing resistance is assumed to be uniformly distributed over the section on this line. Evidently these assumptions do not give the real action. Cutting action begins at the surface. The fibers are pushed inward immediately in front of the cutting edge. As this impression is increased, the bearing pressure is extended over a greater surface of the tool, though not uniformly so distributed, and the resultants of the applied forces will be moved away from the line AB. This separation of the applied forces gives a couple, with resulting beam action and horizontal and diagonal tensile and compressive forces. It is evident that the bearing action and resulting impression modify conditions and also that the shearing stresses are not uniformly distributed over the section, and that cutting action may injuriously affect results. A little calculation will show that the bearing pressure for a thin tool would exceed the resistance of the concrete. Besides, a test piece could not be held in the position shown, and a further support will be necessary.

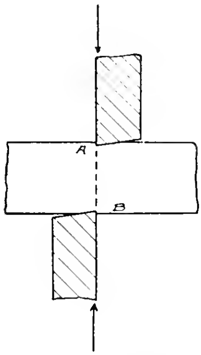


FIG. 1. COMMON CONCEPTION OF SHEAR.

Fig. 2 shows a method which has been proposed and which is open to similar objections. Fig. 3 shows a test piece arranged to get double shear. Evidently the bearing bars, which are only about ¼ in. wide, will produce such high bearing pressures as to cause cutting action or at least cutting stresses. Fig. 4 is a

beam form of test piece. Here the test is complicated by flexural stresses and by deflection or opposition to flexure. The attempts at clamping the ends of the test piece to approximate to a restrained beam, such as are hereinafter described, are also open to objection. Punching tests do not give ideal conditions, as will be seen in the tests of plain plates.

It will be seen that these methods of making tests and of applying the load are open to some objection or other. What is wanted is to get as near ideal conditions as is possible and to approach the conditions which exist in structures under investigation. Take for illustration vertical shear in beams, which forms one of the most common and most important applications for the values to be obtained for shearing resistance. In this case, bearing stresses have little effect. Cutting action does not exist. The vertical shearing stresses are nearly uniformly distributed over the section below the neutral axis and vary only moderately over the compression area. (See Bulletin No. 4, p. 20.) Again attention should be called to the inconsistency of using the terms "shear failure" and "diagonal shear failure" in the case of beams failing by diagonal tension.

This bulletin records the results of shear tests made in the Laboratory of Applied Mechanics of the University of Illinois, together with statements of other available data. It is known that the methods used in the tests and the forms of test pieces used are open to objection, but investigations of this kind are experimental in methods as well as in materials, and the experiments in methods are of themselves of value. It is believed, too, that the results, when compared with those made elsewhere, will go toward establishing the general or comparative value of the shearing strength of concrete, and that no end would be subserved in holding the results for more complete data.

The tests were made principally as thesis work. The tests of 1905 were made by C. S. O'Connell and J. E. Shoemaker of the class of 1905 in civil engineering; those of 1906 by J. E. Schoeller and N. E. Seavert of the class of 1906. These men are entitled to credit not only for the care and industry displayed in their work but for the thought and study given to the problem. Acknowledgment is made to V. R. Fleming, 1905, for aid in the preparation of this bulletin.

Data from Various Sources.

Before taking up the University of Illinois tests, a few pages will be devoted to data taken from various sources and to a brief examination of these data.

It has already been stated that the prevailing notion among engineers is that the shearing strength of concrete is comparatively low. The text-books on concrete and reinforced concrete quote values equal to, or a little more than, the tensile strength of concrete and but a small part of the compressive strength. In the following data, instead of referring to the original publication of the experiments, reference is generally made only to the books which may be available to the general reader.

A set of tests on shearing strength of mortar which have been frequently quoted was made by Bauschinger* in 1878. The test specimens were taken from test pieces 2.4 in. × 4.8 in. × 12 in. which had been broken in flexure. The results were interpreted to show that the shearing strength of the mortar was 20% greater than the tensile strength of similar mortars. It seems probable that in the method of testing used tension and not shear was the controlling element. Results of later tests seem to indicate that these values are not representative of the resistance of portland cement mortar in simple shear.

Marsh† quotes Feret as concluding "that the ultimate shearing resistance is proportional to that for compression, and obtains the relation that the shearing resistance is from 0.16 to 0.20 of the compressive strength; this would give us, taking 2175 pounds per square inch, (the mean compressive resistance at from four to six weeks) a shearing strength of from 350 to 435 pounds per square inch, and at a period of three months from 415 to 520 pounds per square inch".

Marsh also makes the following statement: "In a paper presented at the 1901 Budapest Congress, M. Considère gives the value of the resistance of concrete to shearing deduced from M. Mesnager's experiments as from 20% to 30% higher than the tensile resistance; this gives, taking the values from 260 to 285 pounds per square inch, as the mean at a period from four to six weeks, and 310 to 340 pounds per square inch at three months, which are

* Sabin's Cement and Concrete, p. 328. Falk's Cements, Mortars and Concretes, p. 27.

† Marsh's Reinforced Concrete, p. 222.

TABLE 1.*

STRENGTH OF PORTLAND CEMENT MORTARS.

BY R. FERET.

Item	Approximate Proportion by Weight		Ultimate Strength lb. per sq. in.			Ratio of Shear to Compression
	Cement	Sand	Shear	Tension	Compression	
1	1	18.6	170	69	240	.71
2	1	9.9	570	146	870	.66
3	1	6.9	1070	212	1540	.70
4	1	5.2	1440	258	2350	.61
5	1	4.1	2000	314	3320	.60
6	1	3.2	2560	367	4170	.61
7	1	2.5	2790	421	5210	.54
8	1	1.8	3580	480	5970	.60
9	1	1.2	3930	537	6670	.59
10	1	0.7	3640	563	6810	.65
11	1	12.9	256	81	310	.83
12	1	7.0	669	182	950	.70
13	1	5.0	1040	240	1510	.69
14	1	4.1	1350	278	1990	.68
15	1	3.1	1810	320	2720	.67
16	1	2.5	2250	368	3430	.66
17	1	2.0	2650	415	4380	.61
18	1	1.4	2750	521	5440	.50
19	1	0.9	3580	541	6100	.59
20	1	0.5	3540	602	6720	.53
21	1	12.3	156	67	160	.97
22	1	5.8	370	126	540	.69
23	1	3.5	768	214	1230	.62
24	1	2.4	1410	302	1940	.73
25	1	1.8	2130	364	2840	.75
26	1	1.3	2570	436	3710	.69
27	1	1.0	2750	510	5000	.55
28	1	0.7	3070	574	5760	.53
29	1	0.5	3570	647	6500	.55
30	1	0.3	4120	691	7110	.58
31	1	5.0	1720	328	2350	.73
32	1	3.0	3100	450	4010	.77
33	1	2.0	3070	518	4810	.64
34	1	3.0	....	456	3640	...
35	1	0.0	3680	698	8040	.46

* Taken from Concrete, Plain and Reinforced, by Taylor and Thompson, p. 136.

considerably below those found by M. Feret. Many authors assume that the resistance of concrete to shearing is less than its resistance to tension, and consequently give it a much lower value, but this assumption appears to be erroneous."

Taylor and Thompson* give data from Feret's investigation which indicate a much higher shearing strength for mortar than that given in the preceding paragraph. Table 1 gives the shearing, tensile, and compressive strength of these mortars. It will be seen that the shearing strength ranges from 46% to 97% of the compressive strength and is three to six times the tensile strength.

The method of testing (see Fig. 2) may be open to criticism. The specimen is subjected to single shear, and the small bearing area may produce excessive compressive stresses. Tensile stresses may govern the failure.

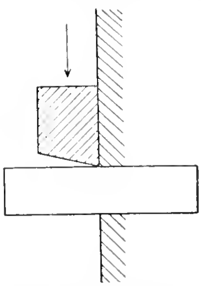


FIG. 2. SHEAR TEST USED BY FERET.

Considère † states that the experiments made by Mesnager tend to show that the resistance of mortar to shearing exceeds its tensile resistance as it is determined by the usual tests. Tests, which may be too few to allow of general conclusions, have shown a difference of 20% to 30% between these two resistances. Marsh ‡ quotes Considère as applying the same statement to concrete.

Falk § gives values of the shearing strength of concrete ranging from 65 to 314 pounds per square inch, and amounting to 10% to 18% of the compressive strength of the concrete.

* Taylor and Thompson's Concrete, Plain and Reinforced, p. 136, taken from "Etudes sur la Constitution Intime des Mortiers Hydrauliques", in Bulletin de la Societe D'Encouragement pour L'Industrie Nationale, 1897. Series 5, Vol. 11, p. 1591.

† Considere's Reinforced Concrete, translated by Moisseiff, p. 101.

‡ Marsh's Reinforced Concrete, p. 222.

§ Falk's Cements, Mortars and Concretes, p. 95. Figure showing method of test, p. 87.

TABLE 2.*

SHEARING AND CRUSHING STRENGTH OF 1-3-5 CONCRETE.

BY M. S. FALK.

No.	Ultimate Crushing Resistance		Ultimate Shearing Resistance		Ratio of Shear to Compression
	Of 6-inch cube lb. per sq. in.	Age days	lb. per sq. in.	Age days	
1	1870	177	195	169	.10
5	....	...	314	165	...
6	1246	164	166	164	.13
8	1196	157	187	157	.15
10	863	151	158	151	.18
22	922	128	104	128	.11
23	600	128	65	128	.11

Table 2 summarizes the data. The method of making the shearing test (Fig. 3) is open to criticism, particularly in that the high bearing stresses cause a cutting action, and the failure of the specimens can hardly be said to be due to shear. The values obtained can not be considered to be representative of the shearing strength of concrete.

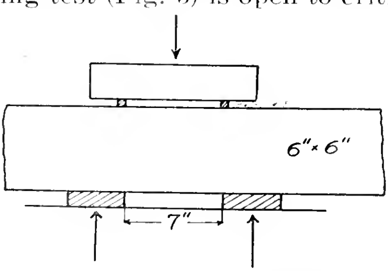


FIG. 3. SHEAR TEST USED BY FALK.

Tests made by Zipkes† on prisms 7 × 7 × 15.8 in. gave values of 357 pounds per square inch for shearing strength of concrete 50 days old. The prisms were supported but not clamped, and the conditions resemble beam failure so much that the results can not be considered to represent ordinary shearing strength. Fig. 4 shows the form of test specimen.

* Taken from Cements, Mortars and Concretes, by Falk, p. 95.

† Beton und Eisen, January, 1906, p. 15, et seq. Translation printed in Cement, March, 1906.

Tests on slotted concrete beams reported in the same article are open to the objection that web stresses other than shearing stresses probably were the cause of the failure.

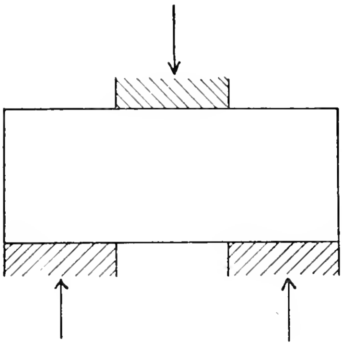


Fig. 4. Shear Test Used by Zipkes.

A valuable set of tests on the shearing strength of concrete was made at the Massachusetts Institute of Technology under the direction of Professor Spofford and the auspices of the Joint Committee on Concrete and Reinforced Concrete in 1905. A summary of the data is given in Table 3. Three grades of concrete were used and test pieces were stored in air and also in water. The cylindrical test piece was 5 in. in diameter and $15\frac{1}{2}$ in. long and the ends were securely clamped above and below in cylindrical bearings. The load was applied along a length of $5\frac{7}{16}$ inches of a semi-cylindrical bearing block. This manner of testing permitted the test piece to break first as a beam but final failure was by shear. Tensile stresses may have affected the results somewhat; if so, the values given are less than the true shearing stength.

TABLE 3.

Summary of Shear Tests.

Made at Massachusetts Institute of Technology.

Kind of Concrete	Method of Storing	Shearing Strength lb. per sq. in. Maximum	Minimum	Average	Crushing Strength lb. per sq. in.	Ratio of Shear to Compression
1-2-4	Air	1630	960	1310	2070	0.63
1-2-4	Water	2090	1180	1650	2620	0.63
1-3-5	Air	1590	890	1240	1310	0.94
1-3-5	Water	1380	840	1120	1360	0.32
1-3-6	Air	1450	950	1180	950	1.25
1-3-6	Water	1200	1030	1120	1270	0.88

MATERIALS, TEST PIECES AND TESTS.

The materials, forms of test pieces, method of testing and phenomena of the tests made at the University of Illinois in 1905 and 1906 will now be described.

Materials.—The broken stone used in the 1905 tests was Kankakee limestone screened through a 1-in. and over a ¼-in. screen. It was taken from the lot described more fully in Bulletin No. 4. The stone for the 1906 tests was similar in character but somewhat harder. The sand was coarse mortar sand, that used in the 1905 tests being the same as that described in Bulletin No. 4 and that used in 1906 being similar in character. The cement used in 1905 was the mixture of American portland cements furnished by the Joint Committee on Concrete and Reinforced Concrete described in Bulletin No. 4. The tensile strength of the neat cement was 723 pounds per square inch at age of 7 days, and 1-3 mortar gave 354 pounds per square inch at 7 days and 533 pounds per square inch at 75 days. The cement used in 1906 was similar in character.

Test Pieces.—As has already been stated, it is extremely difficult to make a test of concrete which will determine the shearing strength. Other stresses, tensile, bearing, and web stresses complicate the problem, and their action may be the controlling element of failure even when shearing action is the apparent cause. The form of test piece to be used was the first point to study, and one purpose of these tests was to find the effect of different forms of test pieces and learn what form is open to the least objection. Two methods of testing were used. In the first, a hole was punched in a concrete plate or block, and this method will be referred to as a punching test. The second method consisted in breaking a short concrete beam which was restrained at the ends. This method will be referred to as the restrained beam test.

Three forms of test pieces were used in the punching tests,—1. plain concrete plate; 2. recessed concrete block; 3. reinforced recessed concrete block. As was to be expected, the plain concrete plate failure indicated that induced tensile stresses contributed to the failure, and the other test pieces were contrived in an attempt to overcome this defect. A cylindrical die 5¾ in. in diameter was used in the punching tests. Fig. 5 (a) shows the dimensions of the plain concrete plate. In the recessed block, shown at (b),

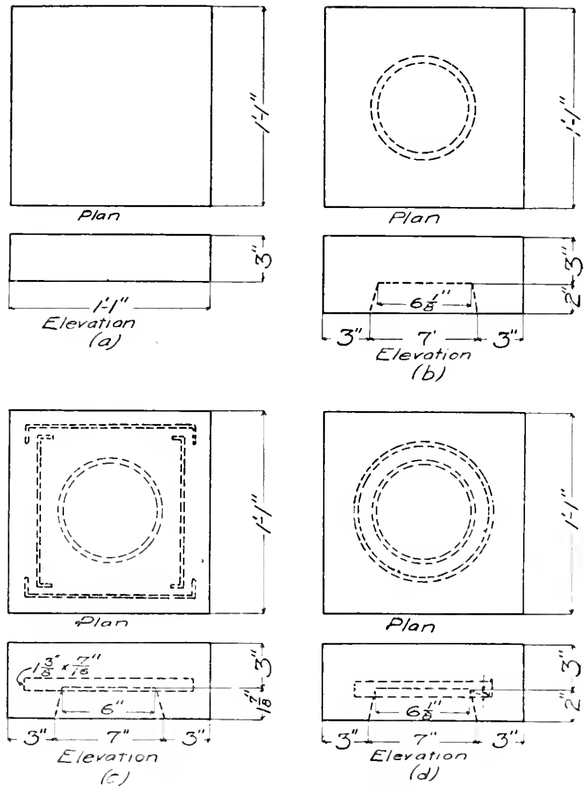


FIG. 5. FORMS OF SHEAR TEST PIECE. (a) PLAIN CONCRETE PLATE. (b) RECESSED BLOCK. (c) and (d) REINFORCED RECESSED BLOCKS.

the shearing area is the same, and the hollow space at the bottom is given a draft in order to facilitate drawing the form. This test piece is better fitted to withstand the tensile stresses developed during the punching operation. Fig. 5 (c) and (d) show the reinforced recessed blocks. A reinforcement of steel was embedded in the concrete. In two specimens tested in 1905 four bent bars, $\frac{7}{16}\times1\frac{3}{8}$-in., were placed as shown in Fig. 5 (c), and in two specimens, eight bent rods, $\frac{1}{4}$-in. square and twisted, were similarly placed.

In making the tests, the test specimens were placed on a bed plate 1 inch thick, having an opening 6 inches in diameter in the center. The load was applied through a spherical bearing block,

and a die $5\frac{1}{4}$ inches in diameter placed on the test specimen formed the punching tool. Plaster of paris coatings were used on all bearing surfaces.

The test piece for the restrained beam test (Fig. 6) was 4 × 4 in. in cross section and 13 inches long. The cast-iron bed plate was faced above and below, as were the two plates at the top.

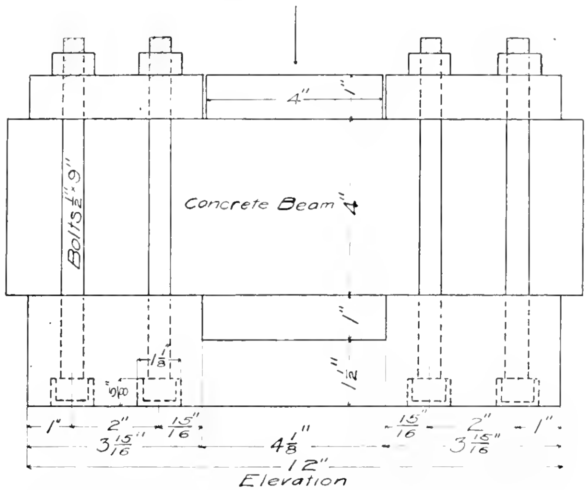


FIG. 6. RESTRAINED BEAM SHEAR TEST PIECE.

TABLE 4.*

COMPRESSIVE STRENGTH OF 6-INCH CUBES.

1905 TESTS. 1-3-6 CONCRETE.

Concrete as in	Method of Storing	Age days	Compression Area sq. in.	Ultimate Load pounds	Compressive Strength lb. per sq. in.
	Air	66	36	48000	1330
Beam No. 35	Air	66	36	47980	1330
	Air	66	36	57400	1590
	Air	67	36	38400	1065
Beam No. 44	Air	67	36	39800	1105
	Air	67	36	29400	816
	Air	59	36	47200	1310
Beam No. 65	Air	59	36	41600	1156
	Air	59	36	48850	1355
Average					1230

* Taken from Bulletin No. 4, p. 32.

The bolts clamped the beam tightly on the bed plate. Plaster of paris coatings were used on all bearing surfaces. Fig. 10 shows the apparatus in testing machine.

TABLE 5.

COMPRESSIVE STRENGTH OF 6-INCH CUBES.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Load in pounds		Compressive Strength lb. per sq. in.
				At First Crack	Ultimate	
1	Damp sand	60	37.9	70000	73200	1930
	Damp sand	60	37.5	72000	73500	1958
	Damp sand	60	36.4	73500	74500	2045
2	Damp sand	60	37.9	58000	86200	2274
	Damp sand	60	37.2	67000	79500	2135
	Damp sand	60	36.4	48000	75600	2072
3	Damp sand	61	37.5	92000	100700	2685
	Damp sand	61	37.1	92000	113600	3060
	Damp sand	61	37.1	78000	109200	2945
4	Damp sand	59	37.1	70400	101000	2722
	Damp sand	59	37.1	84000	101800	2740
	Damp sand	59	37.9	74000	97400	2568
Average						2428
5	Damp sand	60	37.1	59600	65800	1773
	Damp sand	60	37.1	53100	66500	1791
	Damp sand	60	36.8	50100	58900	1600
Average						1721

Compressive Strength of Concrete.—An effort was made to find the compressive strength of concrete in order that comparisons with the shearing strength might be made. The method of making and storing the test pieces was not altogether satisfactory, and for this reason a comparison of strength can not be considered entirely trustworthy. All the cubes tested were 6-in. cubes. In the 1905 tests the concrete cubes were stored in air in a steam heated room where the temperature ranged from 60° to 70° F. Table 4 gives the compressive strength of 1-3-6 cubes of the 1905 tests. In the 1906 tests the concrete cubes were stored in sand

which was kept moist during the period of storage. The results of the test are given in Tables 5 and 6. It will be seen that the values found are very high. In fact, these results are so much higher than other tests of concrete cubes made in this laboratory that the difficulty of comparing the tests with tests made at other times is increased. The cause of these variations is somewhat obscure; the manner of storing is probably only one of the elements

TABLE 6.

COMPRESSIVE STRENGTH OF 6-INCH CUBES.

1906 TESTS. 1–2–4 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Load in pounds		Compressive Strength lb. per sq. in.
				At First Crack	Ultimate	
	Damp sand	59	37.1	109500	128500	3463
6	Damp sand	59	37.1	110000	129000	3480
	Damp sand	59	37.8	73400	121400	3212
	Damp sand	59	35.6	96300	108000	3030
7	Damp sand	59	36.8	104000	117600	3193
	Damp sand	59	37.1	100600	120900	3259
	Damp sand	58	37.5	63400	124700	3322
8	Damp sand	58	37.8	99900	143100	3790
	Damp sand	58	37.8	86800	138000	3650
	Damp sand	59	36.8	79500	91900	2492
9	Damp sand	59	36.4	98000	113700	3120
	Damp sand	59	37.1	69300	99300	2675
	Damp sand	57	37.1	64000	111200	2998
10	Damp sand	57	37.5	59100	98600	2630
	Damp sand	57	37.5	84300	106500	3840

of difference. Tables 7 and 8 give results of the compression tests made on cylinders 8 inches in diameter and 16 inches long. These specimens were of the same material as the 1906 cubes and were stored in the same manner. It will be seen that the compressive strength determined from the cylinder is materially less than that obtained with the cubes. In all compression tests, a spherical bearing block was used, and a coating of plaster of paris was used on the bearing faces.

TABLE 7.

COMPRESSIVE STRENGTH OF 8 x 16-INCH CYLINDERS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Ultimate Load pounds	Compressive Strength lb. per sq. in.
1	Damp sand	60	49.6	60500	1220
2	Damp sand	60	49.6	60000	1210
3	Damp sand	60	49.6	60000	1210
4	Damp sand	61	49.3	80400	1630
5	Damp sand	59	49.4	66200	1340
Average					1322
6	Damp sand	60	49.8	57800	1160

TABLE 8.

COMPRESSIVE STRENGTH OF 8 x 16-INCH CYLINDERS.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Compression Area sq. in.	Ultimate Load pounds	Compressive Strength lb. per sq. in.
7	Damp sand	59	49.6	132000	2660
8	Damp sand	58	49.6	126000	2540
9	Damp sand	59	49.6	114000	2300
10	Damp sand	57	49.6	110000	2220
Average					2430

Discussion.—The behavior of the plain concrete plates and of the unreinforced recessed blocks during the test indicates that tensile stresses were the primary cause of failure with these forms of test specimens. This tension may be likened to the bursting stress developed in a cylinder subjected to internal pressure.

At a load of one-third to one-half of the ultimate load, hair cracks would appear at the bottom and middle of the exterior of the specimen. As the load was increased the crack extended upward and increased in width until at the ultimate load it attained a width of $\frac{1}{16}$ inch at the bottom and extended to the top of the specimen. The specimen could then be broken apart with the hands, giving four exterior pieces and the punched central core. The appearance of the crack is shown in Fig. 8. The broken specimens are shown in Fig. 7. The core which was punched out always showed cracks on the bottom and these generally extended one-half to two-thirds the distance to the top. In some cases the specimen broke into two parts as a beam fails, and in others the corners rose a small distance much as a metal plate does during a punching operation. In every case tension failure at the lateral faces occurred before shearing took place, and it was evident that the final, or ultimate, failure was much influenced by this condition and that ultimate failure could not be said to be due to simple shear. The recessed specimens were better in this respect than the plain plates, and the shearing stresses were evidently more nearly uniformly distributed throughout the depth with this form.

The reinforced recessed blocks failed in a manner quite similar to the unreinforced recessed blocks except that the cracks appeared relatively later and did not open up when the ultimate load was reached. The shearing loads were higher than for the unreinforced specimens and the conditions were more favorable for developing the shearing strength of the material. This is especially true where hoops were used for the reinforcement. An objection which still remains in this form of specimen is that the manner of applying the load at the top of the piece does not give an even distribution of the shear throughout the vertical section.

The manner of failure of the restrained beam form of specimen was as follows: In specimens No. 1 to 5 (1-3-6 concrete) and No.6 (1-2-4 concrete) the first sign of failure was the appearance of cracks at the top as sketched in Fig 11 (a) at a load three-fourths to nine-tenths of the ultimate. These cracks seemed to be caused by a cutting action of the bearing plate or to tension due to beam action. As the load increased these cracks gradually lengthened and widened, as shown in Fig. 11 (b) until they finally reached a

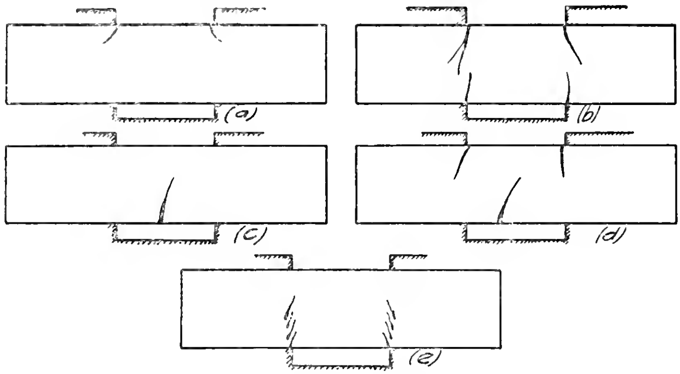


FIG. 11. MANNER OF FAILURE IN RESTRAINED BEAM SHEAR TEST PIECE.

TABLE 9.

SHEARING STRENGTH OF PLAIN PLATES.

1905 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
39	Air	60	55.4	12000	37000	668
40	Air	60	56.5	18000	35000	620
41	Air	61	56.5	15000	39000	691
42	Air	61	56.5	28000	43500	770
43	Air	61	56.5	16000	36000	638
44	Air	61	55.4	14000	35000	632
45	Air	61	56.5	17000	42000	744
46	Air	61	56.5	18000	39500	700
47	Air	61	55.4	19000	36000	650
Average						679
31	Water	69	56.5	8000	36000	637
32	Water	69	54.2	15000	41500	765
33	Water	69	54.2	14000	38400	708
34	Water	61	54.2	12000	36200	667
35	Water	61	55.4	20000	47500	857
36	Water	61	56.5	13000	40000	709
37	Water	61	55.4	17000	42	758
Average						729

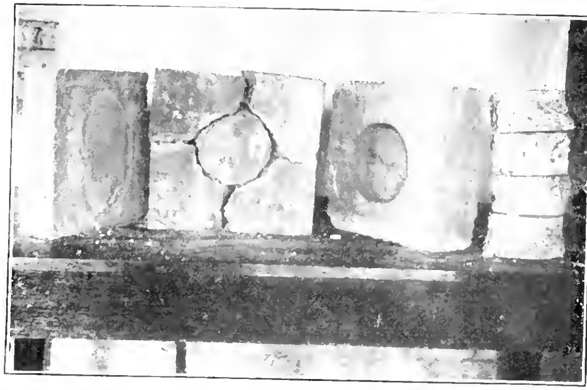


FIG. 7. VIEW SHOWING RECESSED BLOCKS AFTER FAILURE.

FIG. 8. VIEW SHOWING PUNCHING TEST.

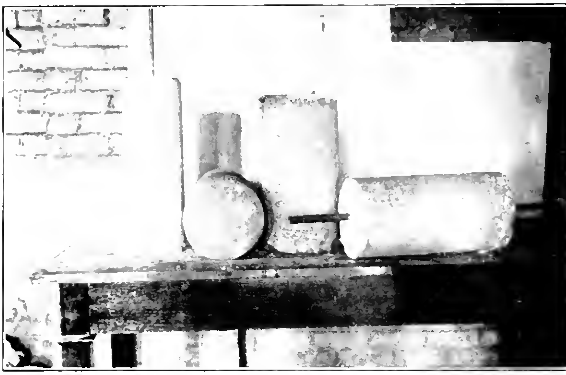


FIG. 9. VIEW SHOWING TEST PIECES.

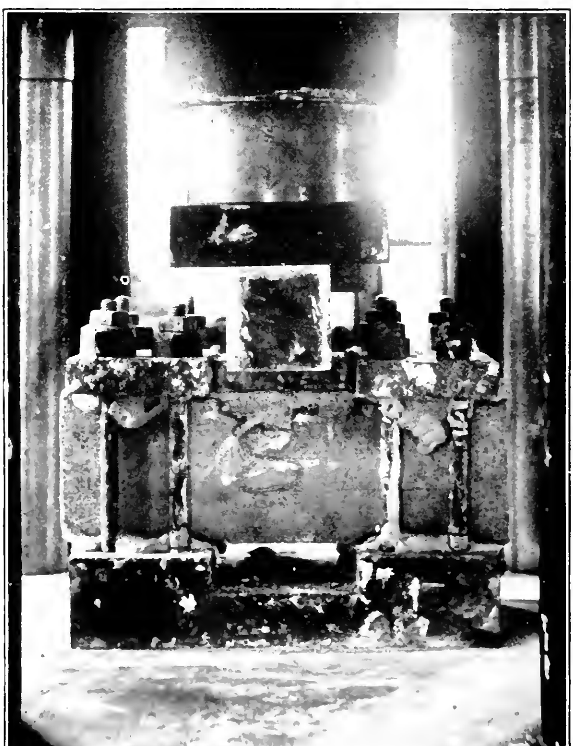


FIG. 10. VIEW SHOWING RESTRAINED BEAM SHEAR TEST.

TABLE 10.

SHEARING STRENGTH OF PLAIN PLATES.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds At First Crack	Load in pounds Ultimate	Shearing Strength lb. per sq. in.
1	Damp sand	60	57.8	28000	30800	533
2	Damp sand	60	61.0	18000	64500	1058
3	Damp sand	61	58.9	58000	60500	1028
4	Damp sand	59	60.1	37800	61200	1018
Average						909
5	Damp sand	60	61.0	39500	59000	968

TABLE 11.

SHEARING STRENGTH OF PLAIN PLATES.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds At First Crack	Load in pounds Ultimate	Shearing Strength lb. per sq. in.
6	Damp sand	59	61.0	24200	81000	1330
7	Damp sand	59	60.1	22000	86800	1443
8	Damp sand	58	58.9	16600	64500	1095
9	Damp sand	59	60.1	12800	48000	799
10	Damp sand	57	61.0	41800	79400	1300
Average						1193

maximum width, of, say, $\frac{1}{32}$ inch at the top. In specimens No. 7 to 10 (1-2-4 concrete) the first sign of failure was a tension crack as shown in Fig. 11 (c), which appeared at a load of one-third to four-fifths of the ultimate and gradually lengthened and widened as the load increased. Later cracks would appear at the top as shown in Fig. 11 (d). After the maximum load was reached, the lower crack gradually closed up and the upper cracks increased in width. The final shearing action occurred at a load less than the maximum and evidently took place over a much smaller shearing

TABLE 12.

SHEARING STRENGTH OF RECESSED BLOCKS.

1905 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per. sq. in.
				At First Crack	Ultimate	
14	Air	60	56.5	23000	51000	903
15	Air	60	56.5	23000	36700	650
16	Air	60	55.4	30000	52500	947
17	Air	60	54.2	21000	34800	642
18	Air	61	56.5	....	39000	691
19	Air	61	55.4	24000	49500	894
20	Air	61	54.2	22000	52500	968
21	Air	61	55.4	26000	49000	894
22	Air	60	56.5	19000	47000	832
23	Air	60	56.5	....	37000	655
24	Air	60	56.5	23000	51500	911
25	Air	60	56.5	19000	41000	725
26	Air	60	54.2	14000	32500	600
27	Air	61	56.5	17500	45500	805
28	Air	61	56.5	18000	40500	717
29	Air	61	56.5	24000	50000	885
30	Air	61	55.4	22000	45500	811
Average	....	.....	....	....	....	796
1*	Water	69	55.4	25000	39500	713
2*	Water	69	54.2	24000	33000	609
3*	Water	69	54.2	25000	36000	664
4*	Water	69	55.4	19500	43000	775
6*	Water	63	55.4	25000	37100	670
8*	Water	61	55.4	....	40000	722
Average		....	....	....	....	692
9	Water	61	54.2	20000	52500	968
10	Water	61	56.5	21000	47200	886
11	Water	61	56.5	24000	50000	885
12	Water	61	55.4	24000	53300	961
13	Water	61	54.2	22000	37700	695
Average	....	....	....	....	....	879

* These specimens were injured in removing the forms.

area than the full section of the beam. At the final failure of these beam specimens cracks formed as shown in Fig. 11 (e) through a portion of the depth. This portion of the vertical section evidently took the full shear.

TABLE 13.

SHEARING STRENGTH OF RECESSED BLOCKS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
1	Damp sand	60	58.8	54000	66300	1126
2	Damp sand	60	58.8	69400	69800	1187
3	Damp sand	61	57.8	63300	69300	1198
4	Damp sand	59	60.1	28000	63300	1052
Average	.....					1141
5	Damp sand	60	60.1	42000	54700	910

TABLE 14.

SHEARING STRENGTH OF RECESSED BLOCKS.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
6	Damp sand	59	60.1	39300	66200	1100
7	Damp sand	59	56.5	45600	82700	1463
8	Damp sand	58	57.8	41100	86500	1495
9	Damp sand	59	58.8	26200	74400	1262
10	Damp sand	57	57.8	19200	55900	967
Average	.....					1257

TABLE 15.

SHEARING STRENGTH OF REINFORCED RECESSED BLOCKS.

1905 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds At First Crack	Load in pounds Ulti-mate	Shearing Strength lb. per sq. in.
48	Air	59	56.5	28000	47000	831
49	Air	59	56.5	36000	65800	1165
50	Air	59	55.4	50000	59000	1065
51	Air	59	56.4	52000	64500	1142
Average						1051

TABLE 16.

SHEARING STRENGTH OF REINFORCED RECESSED BLOCKS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds At First Crack	Load in pounds Ulti-mate	Shearing Strength lb. per sq. in.
1	Damp sand	60	58.5	73000	89500	1529
2	Damp sand	60	57.8	98000	105500	1825
3	Damp sand	61	57.8	100000	108000	1869
4	Damp sand	59	57.8	62300	119100	2060
Average						1821
5	Damp sand	60	58.8	58200	91500	1555

Experimental Data and Discussion.

Data.—Tables 9, 10 and 11 give the results for the form of test piece called plain concrete plates. Tables 12, 13 and 14 give the results for recessed concrete blocks. Tables 15, 16 and 17 give the results for reinforced recessed concrete blocks. Tables 18 and 19 give the results for form of test piece called restrained concrete beam.

TABLE 17.

Shearing Strength of Reinforced Recessed Blocks.

1906 Tests. 1-2-4 Concrete.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds At First Crack	Load in pounds Ultimate	Shearing Strength lb. per sq. in.
6	Damp sand	59	60.1	85300	145500	2420
7	Damp sand	59	55.2	37700	115500	2091
8	Damp sand	58	57.8	64300	160000	2767
9	Damp sand	59	58.8	56700	118000	2008
10	Damp sand	57	58.8	39300	84600	1440
Average						2145

Discussion.—Table 20 gives a summary of the shear tests, together with a comparison with the results of the compression tests. In considering the resistance of concrete to shearing action, as shown by these results, it will be well to take up the effect of the form of specimen upon the phenomena of failure, to consider the values obtained for ultimate failure and the elements which affect the shearing strength of concrete, and to compare shearing strength with compressive strength.

The tests bring out the difficulties of making shear tests. Even the best forms of test piece used proved not fully satisfactory for determining the strength of concrete in simple shear, and in particular their action does not conform exactly to the phenomenon as it exists in beam action. The tests throw light on the subject, and we may expect to be able to form a judgment on the shearing strength of concrete. In the plain plate test specimen the failure in tension caused by the bursting action evidently

TABLE 18.

SHEARING STRENGTH OF RESTRAINED BEAMS.

1906 TESTS. 1-3-6 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
1	Damp sand	60	34.0	....	40500	1190
2	Damp sand	60	35.0	41200	48000	1371
3	Damp sand	61	34.0	46000	46500	1368
4	Damp sand	59	34.0	33300	45000	1324
Average	....	....	....	....	....	1313
5	Damp sand	60	34.0	34000	34700	1020

TABLE 19.

SHEARING STRENGTH OF RESTRAINED BEAMS.

1906 TESTS. 1-2-4 CONCRETE.

Ref. No.	Method of Storing	Age days	Shearing Area sq. in.	Load in pounds		Shearing Strength lb. per sq. in.
				At First Crack	Ultimate	
6	Damp sand	59	35.0	....	54000	1543
7	Damp sand	59	34.0	31500	44000	1295
8	Damp sand	58	34.0	46400	58400	1718
9	Damp sand	59	34.0	33400	49300	1450
10A	Damp sand	57	34.5	29800	45800	1327
10B	Damp sand	57	34.5	27000	40500	1175
Average	....	....	....	....	....	1418

weakened the piece to resist shear, and the results are lower than the real shearing strength of the concrete. In the recessed blocks the bursting effect is distributed over a greater area. The reinforced recessed blocks resisted the bursting pressure even better. The 1906 test pieces reinforced with hoops showed the exterior cracks at a load well up to the ultimate load and these cracks did not open up when the ultimate load was reached. This form is the best of those used in the punching tests. Objection may be made to the punching test that the specimen does not have full opportunity to expand laterally, but a greater objection is that the shearing stress is not distributed uniformly over the shearing area. It is possible that in the specimen reinforced with a hoop the restraint interfered with shear action. The phenomena are further complicated by the compression put upon the test piece and its distribution. In the restrained beam form of test specimen, tension and cutting cracks decreased the effective shearing area. Besides, the application of the load at the level of the top of the beam does not permit an even distribution of the shear throughout the given vertical section. It seems evident that the real shearing strength of concrete will be greater than this form of specimen will give.

In discussing the results given in Table 20, the diverse nature of the materials, the methods of storage, and the form of specimen must be borne in mind. The stone used in the 1906 tests was harder than in the 1905 tests, and the concrete was much stronger. The air-stored specimens were weaker than those not exposed to drying out. The richer mixture does not give proportionally higher strengths than the leaner one. This is to be expected, since the strength of the stone must exert a considerable influence upon the shearing strength and may limit the resistance to shear. The higher values found in the tests made at the Massachusetts Institute of Technology in 1905, as compared with the 1904 results referred to in Taylor and Thompson's Concrete, are explained as due to the better quality of stone used. The quality of the cements used may have had something to do with the difference. It must be remembered that these tests are not entirely comparable. However, it would seem that the results of all these tests may be interpreted to mean that the shearing resistance of concrete is as high as, and probably higher than, the

TABLE 20.

SUMMARY OF SHEAR TESTS.

Form of Specimen	Year	Kind of Concrete	Method of Storing	Number of Tests	Strength lb. per sq. in.			Ratio of Shear to Compression	
					Shear	Compression		Cube	Cylinder
						Cube	Cylinder		
Plain plate	1905	1-3-6	Air	9	679	1230		.55	....
	1905	1-3-6	Water	7	729	1230	......	.59	....
	1906	1-3-6	Damp sand	4	905	2428	1322	.37	.68
	1906	1-3-6	Damp sand	1	968	1721	1160	.56	.83
	1906	1-2-4	Damp sand	5	1193	3210	2430	.37	.49
Recessed block	1905	1-3-6	Air	17	796	1230	......	.65	....
	1905	1-3-6	Water	6	692*	1230	.....	.56	....
	1905	1-3-6	Water	5	879	1230	......	.71	....
	1906	1-3-6	Damp sand	4	1141	2428	1322	.47	.86
	1906	1-3-6	Damp sand	1	910	1721	1160	.53	.78
	1906	1-2-4	Damp sand	5	1257	3210	2430	.39	.52
Reinforced recessed block	1905	1-3-6	Air	4	1051	1230	......	.86	....
	1906	1-3-6	Damp sand	4	1821	2428	1322	.75	1.38
	1906	1-3-6	Damp sand	1	1555	1721	1160	.90	1.39
	1906	1-2-4	Damp sand	5	2145	3210	2430	.67	.88
Restrained beam	1906	1-3-6	Damp sand	4	1313	2428	1322	.54	1.00
	1906	1-3-6	Damp sand	1	1020	1721	1160	.59	.88
	1906	1-2-4	Damp sand	6	1418	3210	2430	.44	.58

* Specimens injured in removing the forms.

values found with the recessed blocks in the punching tests and with the restrained beam test. The shearing strength of this limestone concrete at 60 days, as determined by these methods, may then range from 800 to 1100 lb. per sq. in. for the stone used in 1905 and from 1100 to 1300 lb. per sq. in. for the stone used in 1906, both for 1-3-6 mixtures. For the 1-2-4 mixture with the stone used in 1906, the range is from 1250 to 1400 lb. per sq. in. These agree fairly well with the results obtained at the Massachusetts Institute of Technology in 1905. The reinforced recessed blocks of Table 17 give averages of 1768 and 2145 lb., so that the shearing strength may be higher than the results given above.

It seems evident that the shearing strength is far greater than the tensile strength and comparison of these two properties is not advisable. It does not seem profitable to compare shearing strength with compressive strength, since the former is more largely influenced by the strength of the stone and the latter by the strength of the mortar. The tests made with the recessed blocks, the reinforced recessed blocks, and the restrained beam test specimens indicate that the shearing strength is at least 50% as much as the compressive strength, except that the high results of the 1906 concrete cube tests bring some of the figures below this. These cube tests are much higher than any other of the same mixture made in the laboratory. Comparison with other cube tests and with the cylinders indicates that shearing strength may run well up toward compressive strength. A range which is thought to cover much of the concrete used is 50% to 75%. This conclusion would not disagree with the Massachusetts Institute tests nor with the conclusions of Feret.

Summary.—The following summary is offered:

1. It is difficult to devise a form of test specimen and a method of testing which will satisfactorily determine the resistance of concrete to shear. The difficulties lie in the inability to secure an even distribution of the shear over the shear section, in the high cutting and bearing stresses developed, and in the complications formed by the compressive, tensile, and bulging and bursting stresses developed. The forms of test specimen here used are not fully satisfactory, but information concerning the shearing resistance of concrete may be drawn from the tests as a whole, and tentative values selected. A test specimen in the form of a beam and in which the load is applied evenly over the depth of the beam instead of on the top is suggested.

2. The resistance of concrete to shear is dependent upon the strength of the stone as well as upon the strength of the mortar, and for the richer mixtures the strength of the stone probably exercises the greater influence. With hard limestone and 1-3-6 concrete 60 days old the shearing strength may be expected to reach 1100 lb. per sq. in., and with the 1-2-4 mixture 1300 lb. per sq. in. It seems very probable that the resistance to simple shear is considerably higher than this, and that tests made with the load applied evenly over the shearing section will verify this.

3. Since the compressive strength of concrete is influenced largely by the strength of the cement and the shearing strength is much more influenced by the strength of the aggregate, it does not seem proper to express the shearing strength in terms of the compressive strength. However, this is frequently done and is of advantage in gaining a conception of their relative action. It appears that the shearing strength is, in general, at least 50 % of the compressive strength, and that it may exceed 75 %. The apparent exception to this is explained by the high values obtained in the 1906 compression tests. These conclusions agree in a general way with the statement of Feret and others that the shearing strength is as much as two-thirds of the compressive strength. Evidently the shearing strength of concrete is several times its tensile strength.

II. BOND.

The tests of bond between steel and concrete, or tests of the resistance to a pulling force on the bars, were made in the manner usually followed in such tests. The concrete test piece was made small and short. The tests include the bond resistance of rods having smooth surface and uniform section, like cold rolled shafting, the effect of richness of concrete and of the depth the bar is embedded, and the resistance of flat bars. The work was done by Todd Kirk, a civil engineering student. Mr. Kirk had the misfortune to have the test specimens he made in 1905 injured in the accident mentioned in Bulletin No. 4. The experience gained gives greater reliability to the 1906 tests.

Materials.—The broken stone, sand and cement used were the same as hereinbefore described for the 1906 shear tests. Four different kinds of steel were used: $\frac{1}{2}$-in. and $\frac{3}{4}$-in. round mild steel rods having an elastic limit of about 38 000 lb. per sq. in.; $\frac{1}{2}$-in and 1-in. cold rolled shafting having an elastic limit of about 87 000 lb. per sq. in.; $\frac{3}{4}$-in. round tool steel having an elastic limit of about 53 000 lb. per sq. in.; $\frac{3}{16} \times 1\frac{1}{2}$ in. flat bars with an elastic limit of about 45 000 lb. per sq. in.

TABLE 21.

BOND BETWEEN STEEL AND CONCRETE.

1904 TESTS.

Test No.	Type of Rod		Maximum Load	Area sq. in.	Lb. per sq. in. of Net Section	Lb. per sq. in. of Net Surface	Elastic Limit of Steel	Remarks
1	½-in. Johnson		14990	.20	74950	625	60000	Concrete split.
2	"		14210	"	71050	593	"	" "
3	"	*	12605	"	63000	525	"	" "
27	"	*	15335	"	76650	639	"	Cylinder broke.
4	¾-in. Johnson		17175	.365	47050	573	58300	Concrete split.
30	"		11755	"	32200	392	"	" "
26	"		13975	"	38300	466	"	" "
5	"	*	16360	"	44800	545	"	" "
31	"	*	9515	"	26050	317	"	" "
32	"	*	8960	"	24500	298	"	" "
29	"	*	10435	"	28600	348	"	" "
33	⅜-in. square		4780	.16	29900	250	45000	Rod slipped.
34	"		6850	"	42800	357	"	" "
13	"		5850	"	36550	305	"	" "
35	"	*	6810	"	42600	357	"	" "
36	"	*	6910	"	43200	360	"	" "
18	"	*	4100	"	25600	214	"	" "
14	"	*	5560	"	34700	290	"	" "
8	¾-in. square		11600	.56	20620	322	35000	" "
9	"		11850	"	21100	329	"	" "
10	½-in. square		7910	.27	29320	317	33300	" "
15	"		6400	"	23700	256	"	" "
11	⅜-in. round		3255	.11	28800	228	42500	" "
12	"		3860	"	34200	270	"	" "
16	⅜-in. square	†	6905	.16	43150	180	45000	" "
17	"	†	6690	"	41800	174	"	" "
21	"		4785	"	29930	249	"	" "
22	"		6000	"	37500	312	"	" "
23	"		4580	"	28640	239	"	" "
28	"		6540	"	40800	340	"	" "
7	¾-in. round		7000	.452	15500	245	40500	" "
6	"		11000	"	27500	386	"	" "

* Struck 6 quarter-swing blows with a 10-lb. sledge.

† Embedded for a length of 24 in.

Test Pieces.—Two forms of test piece were used, one a cylinder 6 inches in diameter and 6 inches long, and the other 6 inches in diameter and 12 inches long. In Fig. 9 one of the vertical pieces is a bond test piece. The bars were embedded the full length of the cylinders, one end being left flush with an end of the cylinder and the other end projecting far enough to furnish a grip for the pulling head of the testing machine. The 6-in. length of encasement was used to make sure that the stress in the steel would be far below the elastic limit. It was planned that the stress in the steel in the 12-in. encasement should closely approach the elastic limit. In order to determine the effect of the quality of concrete, two mixtures, 1 cement– 3 sand– 5½ stone, and 1 cement– 2 sand– 4 stone were used, all by loose measure. The 1905 tests were with a 1-3-6 mixture.

TABLE 22.

BOND TESTS.

PLAIN ROUND RODS.

1-3-5½ CONCRETE.

Ref. No.	Diameter inches	Encased Length inches	Surface in Contact sq. in.	Maximum Load pounds	Running Friction pounds	Stress Developed lb. per sq. in.		
						Bond	Running Friction	In Steel
1	½	6	9.42	3400	1850	360	196	17300
2	½	6	9.42	3360	1900	356	201	17100
3	½	6	9.42	3510	1950	372	207	17900
4	½	6	9.42	3555	2000	377	212	18100
5	½	6	9.42	3640	2150	386	228	18500
6	½	6	9.42	3530	2050	375	218	18000
7	⅝	6	11.77	4300	3000	365	258	14000
8	⅝	6	11.77	4195	2600	358	221	13650
9	⅝	6	11.77	4250	2500	361	212	13850
10	⅝	6	11.77	4150	2650	352	225	13520
11	⅝	6	11.77	4075	2500	346	212	13300
12	⅝	6	11.77	4050	2950	342	251	13200
16	½	12	18.84	7130	5400	378	286	36400
17	½	12	18.84	7475	5300	397	281	38100
18	½	12	18.84	6500	4500	345	239	33100
19	⅝	12	23.54	10000	5500	425	234	32700
20	⅝	12	23.54	9500	6000	404	255	30950
21	⅝	12	23.54	8875	5000	377	212	28950

Method of Testing and Age of Test Specimen.—The free end of the bar to be tested was run through the movable head and held in the upper grips of the testing machine. The load was then applied with the movable head. In order that the pressure on the concrete might be uniformly distributed, a bearing plate bedded in plaster of paris was placed between the concrete and the movable head of the machine, the plaster of paris being allowed to set under a small load. The age of test piece when tested was 60 days.

TABLE 23.

BOND TESTS.

PLAIN ROUND RODS.

1-2-4 CONCRETE.

Ref. No.	Diameter inches	Encased Length inches	Surface in Contact sq. in.	Maximum Load pounds	Running Friction pounds	Stress Developed lb. per sq. in.		
						Bond	Running Friction	In Steel
42	1/2	6	9.42	4000	2470	425	263	20400
43	1/2	6	9.42	4490	2600	477	276	22900
44	1/2	6	9.42	4060	2400	428	254	20600
45	1/2	6	9.42	3840	1900	408	202	19600
46	1/2	6	9.42	3650	1700	388	181	18600
47	1/2	6	9.42	3340	1740	355	184	17000
34	5/8	6	11.77	5580	3400	475	289	18200
35	5/8	6	11.77	5510	3390	468	288	18000
36	5/8	6	11.77	5260	3600	448	306	17150
37	5/8	6	11.77	5530	3550	471	302	18000
13	1/2	12	18.84	8200	5500	436	292	41800
14	1/2	12	18.84	6820	5200	362	276	34800
38	1/2	12	18.84	7500	4500	398	239	24400
39	1/2	12	18.84	7900	4730	418	251	25700
15	5/8	12	23.54	11200	7500	476	318	36500
40	5/8	12	23.54	9040	4740	384	202	29450
41	5/8	12	23.54	9000	4000	382	170	29350

1904 Tests.—Table 21 is reprinted from Bulletin No. 1 and gives the results of bond tests made by Mr. Davis in 1904. The concrete used was a 1-3-6 mixture. In making comparisons the values with rods embedded more than 12 inches should not be used, since there is evidently an uneven distribution of bond stress over the length of the bar.

1905 and 1906 Tests.—Tables 22, 23 and 24 give the results of Mr. Kirk's tests. In Table 25 the results are summarized.

Results.—The condition of the concrete caused by the method of testing bond resistance here used, may be considered to differ from the condition of the concrete in a beam when bond stress is developed. In these tests the concrete specimen is subjected to compression, and this compression produces lateral expansion; this lateral expansion may increase the pressure on the surface of

TABLE 24.

BOND TESTS.*

VARIOUS TYPES OF BARS.

Ref. No.	Kind of Steel	Size of Bar inches	Kind of Concrete	Surface in Contact sq. in.	Maximum Load pounds	Running Friction pounds	Stress Developed lb. per sq. in.		
							Bond	Running Friction	In Steel
18	Tool	¾ round	1-3-6	14.13	2060	....	147	....	4650
19	steel	¾ round	1-3-6	14.13	2180	....	154	....	4940
20		¾ round	1-3-6	14.13	1993	....	141	....	4510
22	Cold	1 round	1-3-5½	18.84	2700	1500	143	80	3440
23	rolled	"	"	18.84	2200	1000	117	53	2800
24	shafting	"	"	18.84	2810	1270	150	67	3580
25		½ round	"	9.42	1425	550	151	58	7250
26	do.	"	"	9.14	1610	450	170	48	8220
27		"	"	9.42	1395	400	147	43	7130
28	Mild	3/16 x 1½	"	20.25	2260	1440	111	71	8050
29	steel	" "	"	20.25	2550	1700	126	83	9070
30		" "	"	20.25	2800	2000	138	98	9960

* In these tests the steel was encased to a length of 6 inches.

the steel and thus increase the resistance. On the other hand the low compressive stress developed, a maximum of 500 lb. per sq. in. at the top and 0 at the bottom, indicates that the effect of this can not be large.

TABLE 25.

SUMMARY OF BOND TESTS.

No. of Tests	Type of Rod	Size inches	Kind of Concrete	Encased Length inches	Surface in Contact sq. in.	Max. Load lb.	Bond lb. per sq. in.	Running Friction Max. lb	Running Friction lb. per sq. in.	Ratio of Running Friction to Bond
6	Plain round	½	1-3-5½	6	9.42	3498	372	1983	210	57.0
6	do.	½	1-2-4	6	9.42	3893	412	2135	227	55.2
6	do.	⅝	1-3-5½	6	11.77	4170	355	2700	227	64.0
4	do.	⅝	1-2-4	6	11.77	5376	465	3485	297	64.0
3	do.	½	1-3-5½	12	18.84	7035	373	5066	268	72.0
4	do.	½	1-2-4	12	18.84	7605	404	4982	266	65.5
3	do.	⅝	1-3-5½	12	23.54	9458	402	5366	228	56.8
3	do.	⅝	1-2-4	12	23.54	9736	414	5284	223	54.0
3	Cold rolled shafting	1	1-3-5½	6	18.84	2570	136	1256	67	49.2
3	do.	½	1-3-5½	6	9.42	1476	157	466	50	31.8
3	Mild steel	$\frac{3}{16}$x1½	1-3-5½	6	20.25	2536	125	1713	84	67.1
3	Round tool steel	¾	1-3-6	6	14.13	2077	147	......	......	......

The following is given as an interpretation of the results of the tests on — steel bar in compression!

1. Little difference is found in the bond resistance per square inch of surface of bar in contact with the concrete whether the bar is embedded 6 inches or 12 inches. Evidently a length may be found beyond which the stretch of the steel would cause uneven distribution of the bond stress along the length of the bar and cause failure to begin at the point of greatest stress in the steel and thus give results not representative of the real bond resistance. This limitation applies to length for use in experimental tests of bond. In simple beams the bond stresses are applied along the length of the bar, and stretch and bond exist together.

2. The richer mixture of concrete gives somewhat higher bond resistance than the leaner—the values for the 1-2-4 concrete averaging, say, 10% to 15% higher than the 1-3-5½ concrete. For plain round mild steel rods, the average for the bond resistance ranges from 350 to 450 lb. per sq. in. of contact surface.

3. The flat bars gave much lower resistance than round bars. Only three tests were made with flat bars, and these may not be representative. It may be noted that the results with flat bars are much lower than tests made elsewhere. It should also be noted that for a bond stress of 125 lb. per sq. in., the tensile stress developed in the bar was only 9000 lb. per sq. in.

4. The value of bond resistance will depend upon the smoothness of the surface of the bar, the uniformity of its diameter and section, the adhesive strength of the concrete, and the shrinkage grip developed in setting. The effect of smoothness of surface and uniformity of diameter and section is seen in the tests made with cold rolled shafting and tool steel. The average bond developed with cold rolled shafting and tool steel was 147 lb. per sq. in. of contact surface, as compared with about 400 lb. per sq. in. for ordinary plain, round, mild steel rods. It should be stated that not only was there a very noticeable difference in the smoothness and finish of the surface of the rods, but the section of the cold rolled shafting and tool steel was very uniform, the diameter not varying more than .0001 or .0002 in. at ¼-in. intervals throughout the length, while mild steel rods will vary as much as .0015 in. It is to be expected that the smoothness and uniformity of section of drawn steel wire will operate to give low values of bond resistance, though, of course, as the section of wire is small compared

with the circumference, the bond stresses developed when wire is used are relatively small. Attention is called to the fact that in the reinforced concrete beams described in Bulletin No. 4 the bond stresses developed in beams failing by tension of the steel, diagonal tension of the concrete or other similar methods amounted to from 73 to 193 lb. per sq in. Even at the breaking load, then, the bond stress developed in the mild steel rods was far below the bond resistance found in these tests.

5. In these tests the bars began to slip when the maximum load was reached. After slipping began, the resistance to motion was still considerable. This running friction, taken when the bar had moved about ¼ in., amounted to 54% to 72% of the bond developed in the case of mild steel bars and to 32% to 49% in the case of the cold rolled shafting.

Publications of The Engineering Experiment Station

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.

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AN EXTENSION OF THE DEWEY DECIMAL SYSTEM OF CLASSIFICATION APPLIED TO THE ENGINEERING INDUSTRIES

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I. Introduction.

1. *Preliminary.*—The decimal system of classification was devised and elaborated by Mr. Melvil Dewey, formerly director of the New York State Library. This system was intended primarily for the use of librarians in the classification and arrangement of books and pamphlets, but it was soon found that the system furnished also a simple and effective means of classifying, indexing and filing literary matter of all kinds. Engineers have found it useful for indexing technical data and information, catalogs, reports, card systems, drawings, etc., and it has been found equally useful by manufacturing and business concerns.

Recognizing the value of the decimal system as a means of classifying and indexing technical literature, the department of mechanical engineering of the University of Illinois prepared several years ago an extension of that part of the Dewey classification which relates to mechanical engineering. The first edition was a small pamphlet of six pages. The demand for the extension was so great that within a year a second edition was printed, and this has been followed by the third and fourth editions. In each successive edition the extension has been carried somewhat further, and such slight changes and modifications have been made as would add to the clearness and consistency of the system as a whole. In the third edition was incorporated with slight modifications the extensions for railroads and railroad engineering adopted by the International Railway Congress.

In the fourth edition are included the extensions to mechanical and railway engineering already worked out; an extension for electrical engineering made by Mr. J. M. Bryant of the electrical engineering department; and more or less complete extensions for other branches of engineering. The whole will be, it is hoped, a self-contained classification which will cover with fair completeness the entire ground of engineering industry.

2. *Explanation of the Decimal System.*—The essential characteristic of the Dewey system is its method of division and subdivision. The entire field of knowledge is divided into nine chief classes numbered by the digits from 1 to 9. Matter of too general a nature to be included in any of these classes is put into a tenth class and indicated by 0. The following are the primary classes of the Dewey system:

0 General Works
1 Philosophy
2 Religion

3 Sociology
4 Philology
5 Natural Science
6 Useful Arts
7 Fine Arts
8 Literature
9 History

Each of these classes is again divided into nine divisions, with a tenth division for general matter, and each division is separated into nine sections. The sections are again sub-divided and the process may be carried as far as desired.

To show clearly the working of the system the divisions of class 6 (useful arts) and the sections of division 2 of this class (engineering) are given.

600	Useful Arts	620	Engineering
610	Medicine	621	Mechanical
620	Engineering	622	Mining
630	Agriculture	623	Military
640	Domestic Economy	624	Bridge and Roof
650	Communication and Commerce	625	Road and Railroad
660	Chemical Technology	626	Canal
670	Manufactures	627	River and Harbor
680	Mechanic Trades	628	Sanitary: Water Works
690	Building	629	Other Branches

It will be seen that the first digit gives the class; the second, the division; and the third, the section. Thus 625 indicates section 5 (railroad engineering) of division 2 (engineering) of class 6 (useful arts). For convenience a decimal point is inserted after the section digit. Further sub-division is indicated by digits following the decimal point. For example 625.2 is the number indicating rolling stock; 625.23 passenger cars; 625.24 freight cars, etc.

3. *Relative Index.*—Following the classification is the relative index, in which the items of the classification are arranged alphabetically, each with its proper class number. The index is necessarily incomplete, as it is manifestly impossible to include every subject that might arise in engineering practice.

In a highly specialized industry, as for example, the electrical industry, there are thousands of technical terms indicative of materials and processes and to include these would alone require

a volume. It is believed that the index is sufficiently complete that the user may without difficulty assign the proper number to almost any topic that may arise.

In some cases, the same item has two numbers. For example, "Telephones" has the numbers 537.82 and 654.6. Reference to the classification shows that the former number is used when the telephone is considered as an application of the electric current, while the latter is used when the telephone is looked upon as a means of communication. In any case, reference to the classification will show which number is appropriate to the item under consideration.

4. *Uses and Advantages of the Classification and Index.*—The decimal classification may be used to advantage in the indexing and filing of notes and memoranda, clippings, general information, articles in technical journals, drawings, catalogs or books. For this purpose, the decimal system possesses certain important advantages over the alphabetical system.

(1) It groups allied subjects. For example, suppose the alphabetical arrangement to be applied to a case of catalogs. The catalogs of the various machine tools, as planers, lathes, drills, hammers, etc., would be scattered throughout the case. With the decimal system, on the other hand all these catalogs would be grouped together under the class number 621.9.

(2) Unless an elaborate system of cross reference is used, the alphabetical scheme is ambiguous; in many cases there is doubt as to what letter should be given a subject. For example, take the item "Automatic pneumatic block signals." This might almost equally well be indexed under A, P, B or S. With the decimal system this item has its one number 656.256.4.

(3) The decimal system has the advantage of flexibility and an indefinite capacity for extension. For the indexing of books and catalogs only the main division and sections will, in general, be found necessary; but for card indexes of technical literature the most minute subdivisions must ordinarily be used. In individual cases, the user may find that still further division is required. An extension may then be made by adding another decimal place, and if still further subdivision is required still another digit may be used.

The average engineer, for example, can easily index all matter relating to traveling cranes under the single class number 621.872. The designer or builder of cranes may, however, have so much matter relating to this special subject that further subdivision is needed. By the addition of a digit, this matter may

be divided into nine groups designated by 621.872.1, 621.872.2, etc.; and, if necessary, each of these may be divided into nine new groups.

The effectiveness of the Dewey system has been severely tested in the Engineering College of the University. The mechanical engineering department has a card index of current periodical literature which now contain 20,000 cards. These are indexed by the Dewey system. The classification is first made by students, and is then revised by one competent person. It seldom occurs that there is any doubt as to the proper class number for a given card. For the guidance of those who may wish to use the classification in connection with a card index a sample card is shown on page 8. The class number 621.63 serves to locate the card in the case and the remaining notes in the margin indicate the periodical, volume, page and date. Thus the article in question appeared in the Proceedings of the Institution of Civil Engineers, Vol. 123, page 272, December, 1895; it occupies 55 pages and has 31 illustrations.

Blue prints received from manufacturers; all catalogs, of which there is a large number; clippings, photographs and illustrative class room material; all these are indexed and filed by the decimal system. In every case the system has been found thoroughly satisfactory.

5. *Variations and Modifications.*—In the working out of the extension of the various subjects the main divisions and sections as published by Mr. Dewey have been retained unchanged. It cannot be denied that there are many glaring inconsistencies in the arrangement of engineering subjects. For example, no engineer of to-day would put electrical engineering as a division under mechanical engineering (621.3) coordinate with blowing and pumping engines (621.6); nor would he relegate concrete to an unimportant place under building materials. There is no doubt that a committee of competent engineers could vastly improve the logical arrangement of the class numbers for engineering subjects. However, the system as it is, with its faults, has been in use several years and has become more or less universal. It is used in libraries and by many business concerns and individuals. It has become a sort of a standard like the Sellers system of screw threads. For this reason alone, radical changes would be inadvisable. The inexperienced user will be likely to see room for improvement and will be tempted to make changes in the system for his individual use. Such changes can only lead to confusion. It is far better to accept the system merely as an arbitrary set of numbers cor-

responding to certain topics and resolutely dismiss rigid ideas of logical sequence and consistency.

There are certain permissible modifications, however, which may be made without violating the integrity of the system. To avoid the writing of long numbers a single letter may be used for the first three or four digits. Thus an electrical engineer would naturally have most of his material under 621.3 (electrical engineering), and for this number he could substitute the single letter E. Likewise, a railroad man might use R for 625 (railroad engineering).

Another modification consists in the use of an alphabetical arrangement for certain sub-sections combined with the decimal arrangement of main sections. This is sometimes useful in minute subdivisions. For example, under 621.728, material and supplies for the foundry, these various materials may be arranged in alphabetical order.

The use of form divisions is a modification that may often be employed to advantage. There are certain set forms that are used throughout the whole range of the Dewey classification. These are:

01 Philosophy or theory
02 Compends, text books, etc.
03 Cyclopedias, dictionaries
04 Essays, addresses
05 Periodicals
06 Societies
07 Education, teaching schools, colleges, universities
08 Tables, calculations miscellanies
09 History progress and development

These forms may be further extended; thus:

064 Exhibits, etc. (under societies)
072 Laboratories (under universities)

Other form divisions which apply particularly to engineering are the following:

001 Statistics
002 Quantities and costs
003 Contracts and specifications
004 Designs and drawings
005 Executive
006 Working and maintenance

007 Laws
008 Patents
009 Reports

These form divisions may be enclosed in parentheses and annexed directly to the usual class number. Thus 62 (07) indicates engineering education; 621.32 (09), progress of electric lighting; 621.57 (008), patents on ice-making machinery, etc. The object of this parenthesis separation of the form divisions is convenience in cross-references. For example if one is interested in patents he may write his class numbers as follow:

(008)62 Patents—Engineering
(008)66 Patents—Chemical technology
(008)69 Patents—Building

In this way all cards on patents are grouped together.

Other modifications will suggest themselves to the user as he becomes more familiar with the system.

6. *Acknowledgments.*—The authors are much indebted to Mr. J. M. Bryant for his work on the extension of electrical engineering and to Mr A. L. Voge, Washington, D. C., for valuable criticisms and suggestions.

Sample Card from Card Index

621.63 Proc. I. C. E. V. 123 p. 272 Dec.	'95	The Design and Testing of Various Types of Centrifugal Fans (55 p. 34i) H. Heenan and W. Gilbert Gives results of elaborate experiments on the efficiency of fans, and deduces characteristic curves that may be employed in the design of a fan with maximum efficiency for a given duty.

Abbreviations Used on Index Cards

pages	p
diagrams, sketches, etc	d
curves, plots, or groups of same	c
illustrations, photographs, etc	i
tables of data, etc	t
words	w
volume	v

TABLE
OF
CLASS NUMBERS

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331	Capital Labor and Wages
.1	Relations of Capital to Labor
.2	Wages Profit sharing Compulsory insurance
.3	Labor of children
.4	Labor of women
.5	Convict labor Prison contracts
.6	Pauper labor Cheap foreign labor
.7	Skilled and unskilled labor
.8	Laboring classes
.81	Hours of labor
.82	Places of labor Dangers
.83	Food Clothes Shelter
.84	Morals and habits
.85	Helps Lectures, libraries, reading rooms, etc.
.86	Training Apprenticeship
.87	Organization of labor
.88	Trades unions
.89	Strikes
370	Education
380	**Commerce Communication**
385	Railways from the Economic and Financial Point of View

385.0 General works
(Compends, Essays. Periodicals, Societies, Reports, Statistics, History)

.1 Railways from the financial point of view

.2 Competition of railway and steamship lines

.3 State control of railways

.4 Administrative organization of railways

.5 Personnel
(Relations of railroads to employes, etc.)

.6 International agreements relative to railroads

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387 River and Ocean Transportation

388 Rapid Transit in Cities

389 Weights and Measures

510 Mathematics

511 Arithmetic 512 Algebra 513 Geometry 514 Trigonometry 515 Descriptive Geometry and Projection 516 Analytical Geometry 517 Calculus 519 Probabilities

520 Astronomy

530 Physics

531 Mechanics

.1 Pure motion Kinematics

.2 Statics Graphic statics

.21 Force and its measure
(Traction dynamometers, weighing scales, etc.)

.3 Dynamics Kinetics

.4 Work Friction
(Friction brakes Transmission and absorption dynamometers)

.5 Gravity

.6 Conservation of energy

.7

.8 Machines Transmission of force

531.9 Tables Problems Questions

532 Liquids Hydrostatics Hydraulics

.5 Liquids in motion Flow in pipes, channels. etc.

533 Gases Pneumatics Air

.1 Properties of gases and vapors

.2 Laws of compressibility

.3 Atmosphere

.6 Aeronautics

.7 Kinetic theory of gases

534 Sound Acoustics

535 Light Optics

536 Heat

.1 Theory Nature

.2 Communication

.3 Action of bodies on heat
(Reflection, refraction, radiation, absorption)

.4 Effects Action of heat on bodies

.46 Combustion

.5 Temperature Measurement of, etc.

.51 Thermometry

.52 Pyrometry

.53 Electric methods of measuring

.6 Calorimetry

.7 Thermodynamics

.71 The perfect gases

.72 The vapors

.73 Thermodynamics of the steam engine and other heat motors

.74 Flow of fluids

.8 Applications

.9 Tables Problems Questions

537 Electricity

.1 Theory Nature

.2 Statical

.3

.4 Atmospheric Lightning rods

.5 Dynamical

.6 Electrodynamics

.7 Electrical measurements

.8 Applications (See 621.3 etc.)

.81 Telegraph (See 654)

.82 Telephone Microphone (See 631.35)

.83 Dynamos Electric lighting (See 621.31)

.84 Transmission of power Storage (See 621.34)

.85 Electro-metallurgy

.86 Galvanometers

.87 Medicine

.88 Electric signals

538 Magnetism

539 Molecular Physics

.1 Theory Molecular structure

.2 Properties of Solids

.3 Elasticity Torsion

.4 Strength of materials

(See also 620.1. General theory should go under 539.4; tests and results of tests, under 620.1)

540 Chemistry

549 Mineralogy

550 Geology

553 Economic Geology

.1 Ore deposits

553.2 Carbon series

.21 Peat

.22 Lignite and jet

.23 Cannel coal Bituminous shale

.24 Bituminous and semi-bituminous coals

.25 Anthracite and graphitic anthracite coals

.28 Petroleum Natural gas

.3 Ores of iron

.4 Ores of metals other than iron

.5 Building stones

.51 Marbles and limestones

.52 Granites and syenites

.53 Sandstones

.54 Slates

.57 Trap

.6 Earthy economic materials

.61 Fire and brick clays

.62 Sands

.65 Emery

.68 Limes and mineral cement

620 Engineering

62(001) Statistics

62(002) Quantities, costs, etc.

62(07) Engineering education

620.1 Applied mechanics Engineering materials

.11 Strength of materials General theory

.112 Tests Factors affecting strength

.1 General: influence of temperature, selection of test pieces, etc.

.2 Corrosion Weathering Protection against deteriorating influences

.3 Elastic limit tests: plasticity, fatigue deformation

.4 Tension, compression, torsion, flexure, shearing

.41 Tensile tests

.42 Compression tests

.43 Torsion tests

620.112.44 Flexure (transverse) tests
.45 Shearing tests
.46 Repeated stress tests
.5 Impact Repeated shock tests
Crystallization and formation of cleavage planes
.6 Hardness tests
.7 Special tests
Varying for different materials
.8 Tests on special shapes and forms
.82 Plates and structural shapes
Bars, rods, angles, beams: T, bulb, I, and channel beams
.83 Columns, built columns tubes, pipes, cylinders
.84 Rollers Spheres, solid or hollow Ball bearings
.85 Springs
.86 Hooks Chains Hoops Rings
.87 Rivets Bolts Screws Nails
Riveted joints of plates
.88 Wire Wire rope Cables Hawsers
.89 Other forms
.9 Other tests

.12 Tests of timber
.13 Tests of Stone Cement Concrete
.132 Stone
.135 Cement
.136 Concrete
.137 Reinforced concrete
.139 Other: artificial stone

.14 Brick, tile, etc.
.15 Masonry adhesives
Cement, mortar, plaster of paris, etc.
.17 Iron and steel Testing machines
.18 Other metals
.19 Other materials
.195 Mineral: asbestos, mineral wool
.196 Asphalt Tar
.197 Vegetable: paper, hemp, etc.
.198 Animal: hair, hide, bone, etc.
.199

.2 Compends Handbooks

.3 Dictionaries, cyclopedias

.4 Essays

620.5 Periodicals

.6 Societies

.7 Study and teaching Instruments

.8 Tables and calculations

.9 History of engineering

621 Mechanical Engineering

(The same form divisions apply to 621 as to 62 above)

.1 Steam engineering

.101 Applied thermodynamics

.11 Mechanism of steam engine Design of engine parts

.111 General

.112 Types of engines

.12 Marine engines

.121 General

.122 Types of marine engines

.123 Marine steam turbines

.13 Locomotives

.131 Theory of the locomotive

.1 Adhesion Tractive force Horsepower

.2

.3 Tests

.132 Types of locomotives

.133 Locomotive boilers Production of steam

.1 Combustion Fuels Petroleum Fuel consumption

.2 Grate and ash pit Firebox Stays

.3 Shell and tubes

.4 Smokebox and stack

.5 Exhaust pipe

.6 Dome and throttle

.7 Boiler feeding Pumps, injectors Purification of water Scale prevention

.9 Miscellaneous fittings Gage cocks, safety valves, etc.

.134 Engine of the locomotive

.1 Driving mechanism Cylinders, pistons, rods, cranked axles, etc.

.2 Steam distribution Slide valves

.22 Special types of valves and valve gears

.4 The compound principle Distribution in compound locomotives

621.134.5 Lubrication of locomotive
.135 Running gear
.1 Frames Frame plates Transverse bracing, attachments to boiler, etc.
.2 Wheels, boxes, and axles Disturbances Counterbalancing
.3 Suspension Springs, saddles, equalizing levers, etc.
.4 Trucks Bissell trucks, four-wheel trucks, etc.
.5 Locomotive brakes
.136 Tenders
.1 Design of, weight of, brakes, etc.
.2 Coupling arrangements
.3 Taking water without stopping; track tanks; water scoops
.137 Management of locomotive Engineer's and fireman's duties Assignment of crews, etc.
.138 Maintenance and repair of locomotives
.1 Round houses
.5 Locomotive repair shops
.139 Supplies Materials

.14 Traction engines (agricultural, road roller, etc.)
.146 Agricultural: tractors, etc.

.15 Portable engines
.156 Agricultural: threshers, etc.

.16 Stationary engines
.164 Types
.2 Throttling engines
.3 Automatic shaft governor engines
.4 Releasing gear engines (Corliss, etc.)
.5 Single acting engines of Westinghouse or Williams type
.165 Steam turbines
.1 Theory
.11 Methods of calculation
.12 Vanes and buckets
.13 Guide vanes and nozzles
.14 Stresses in rotor or disc
.15 Windage
.2 Types
.21 Velocity turbines
.22 Pressure turbines
.23 Combined velocity and pressure turbines
.3 Construction Details of design

(.32 Vanes, buckets; .33 guide vanes, nozzles; .34 rotor, discs; .35 valves, governors, safety devices; .36 thrust balancing; .37 mass balancing; .38 casing, etc.; .39 bearings, etc.)

.166 Rotary engines

621.167 Hoisting engines, hauling engines, dredge engines, and other special types

.18 Steam generation and transmission
Fuels, furnaces, boilers, piping, power plants
For steam heating see 697.5

.181 General
.182 Fuels Combustion
.2 Fuels for boiler heating
.22 Solid fuels: coal, lignite, wood, sawdust, peat
.23 Liquid fuels: tar, petroleum, alcohol
.24 Gaseous fuels: gas from blast furnaces, coke ovens, natural gas
.25 Composite fuels: city refuse, coal dust, trash
.3 Fuel consumption
Practical experiments with a single fuel
.4 Comparative consumption
Practical experiments with various fuels
.183 Furnaces Draft
.1 General
Heating and grate surfaces
.2 Types of furnaces
.3
.4
.5 Furnace parts and construction details
.52 Grates
.53 Stationary grates
.54 Shaking, dumping and step grates
.55 Ashpits Furnace doors
.57 Burners for liquid fuel
.6 Mechanical stokers
.62 With traveling grate
.63 With rocking grate
.64 With step grate (Roney grate)
.65 With plunger
.66 With screw
.7 Other appliances
.77 Pulverized fuel appliances
.78 Fuel and ash conveyors Ash removers
.8 Chimneys Stacks Draft appliances Smoke consumers
.82 Natural draft Dampers Uptakes
.84 Induced draft
.85 Forced draft
.184 Boilers
.1 General

621.184.13	Boiler economy Tests Feedwater
.2	Types
.22	Marine
.23	Locomotive, traction, portable
.24	Stationary
.25	Firetube boilers (tubular)
.252	Internally fired
.253	Externally fired
.26	Water-tube boilers (tubulous)
.27	Flash generators Instantaneous vaporizing boilers
.5	Boiler construction Setting Parts
.52	Shell Heads Tubesheets Domes Drums Riveted joints, staying and bracing
.53	Tubes Ferules Rings
.54	Casing
.55	Inspection and cleaning parts: man and hand holes, cleanouts, covers
.56	Setting and hanging
.57	Foundations: masonry, flues, etc.
.7	Boiler accessories
.72	Water gauges, floaters, gauge glasses, warning whistles
.73	Pressure gauges, manometers, safety valves
.79	Other: air cocks and blowout valves, zincs, steam collectors
.185	Steam transmission and distribution. Piping
.1	General: laws of flow, condensation, friction
.2	
.3	Connections: mains, auxiliary piping
.4	Valves Stop, safety, reducing Pressure regulators
.5	Drains and traps Rceivers and distributing valves
.6	Covering Insulators Nonconductors for high, low and medium temperatures
.7	Joints and cements Expansion joints
.8	Utilization of exhaust steam

19 Steam boiler and power plants. Central stations

.191	General
.192	Arrangement and housing of apparatus
.5	Provision for enlargement
.193	Care and management of steam apparatus
.194	Boilers

621.194.1 Firing
.2 Feeding
.3 Treatment of feed water: purification, softening
.4 Scale prevention Incrustation
.7 Inspection Hydraulic tests Rating
.195 Engines: oiling, packing, adjusting
.196 Duration Wear
.5 Corrosion
.197 Steam plant accessories Economic appurtenances
.2 Feedwater appliances
Tanks, heaters economizers, filters, purifiers, regulators
.3 Pumps Injectors Return traps
.4 Separators
.5 Superheaters
.6 Condensers and cooling towers
.62 Surface condensers
.63 Jet condensers
.64 Cooling towers
.67 Condenser accessories
.7 Instruments
Indicators, tachometers, gauges, dynamometers, thermometers, pyrometers, lubricators, etc.

.2 Hydraulic engines or motors

General theory of hydraulics (See 532)

.21 Water wheels
.22 Overshot and breast wheel
.23 Undershot wheel
.24 Turbines
.241 General: parts (buckets, guides, regulators)
.242 Reaction or pressure turbines
.247 Impulse turbines

.25 Water pressure engines Accumulators
.252 Hydraulic pumps
.253 Piping for high pressure
.254 Accumulators

.26 Hydraulic machinery and appliances Hydraulic presses
For theory see 532.81
.262 Funicular engines Hydraulic tackle
.263 Hoists Elevators Cranes
.264 Special handling and lifting machinery for steel works, etc.

621.266 Presses Forging and stamping machines
.267 Accessories: injection pumps
.269 Mining, tunneling and other hydraulic appliances
Hydraulic giant, Brandt's hydraulic gun

.27 Hydraulic rams
For theory see physics 532.83
.272 Lifting rams Montgolfier ram, Bolle ram, etc.
.273 Pumping rams Leblanc ram
See also 621.64 Pumps
.274 Compressing rams Sommelier ram

.29 Flood gates Dams Mill sluices Head and tail races

.3 Electrical Engineering

.31-.37 Heavy Current Engineering

.31 Generation of electricity Dynamoelectric machinery Transformers
.311 General
.312 Central stations
.312(001) Generalities, statistics, data, etc.
(002) Economics, costs, current prices, etc.
(003) Specifications
(004) Designs, drawings, etc.
(005) Management
(006) Working and maintenance
(0064) Operation and running
(0065) Regulation and control
(0069) Repairs and renewal
(007) Testing of power plants
(008)
.1 General
.2 Stations for lighting only
.22 Steam driven
.23 Gas driven
.24 Hydraulic
.25 Composite
.3 Stations for traction only
.32 Steam driven
.33 Gas driven
.35 Composite
.4 Stations for power transmission
.42 Steam driven
.43 Gas driven
.44 Hydraulic
.5 Combined stations

621.312.52	Steam driven
.53	Gas driven
.54	Hydraulic
.6	Substations
.63	Transformer substations
.64	Converter substations
.65	Accumulator substations
.313	Dynamo electric machines
(001)	General, statistics, data
(002)	Costs
(003)	Specifications for D.E.M.
(004)	Designs, drawings, specifications
(005)	Construction, installation
(0051)	General details and parts
(0052)	Electrical details
(00522)	Armature windings
(00523)	Field windings
(0053)	Magnetic details
(00532)	Armature cores
(00533)	Field cores
(00534)	Yokes
(0054)	General details
(00542)	Frame, bed plate, etc.
(00543)	Bearings
(00544)	Shafts, pulleys, etc.
(006)	Working, regulation, operation
(0064)	Operation, running
(0065)	Faults, diseases, etc.
(007)	Tests and testing work
(008)	Accessories
(0082)	Commutators
(0083)	Collector rings
(0084)	Brushes
(0085)	Brush holders
.1	General; construction, installation
.2	Direct or continuous current machinery
.21	Theory
.22	General types
.23	Continuous current generators
.24	Continuous current motors
.245	Constant speed motors
.246	Multispeed motors
.247	Adjustable speed motors
.248	Varying speed motors (railway motors)
.25	Continuous current converters
.26	Dynamotors
.27	Compensators or balancers

621.313.28	Continuous current boosters
.29	Other
.291	Acyclic or homopolar machines
.3	Alternating current machinery
.32	General types
.321	Single phase
.322	Two phase
.323	Three phase
.4	Synchronous machines
.41	Theory
.42	General types
.43	Alternating current generators
.44	Synchronous motors
.5	Alternating current converters
.51	Theory
.52	General types Description
.53	Synchronous converters
.54	Phase converters
.55	Frequency changers
.56	Double current generators
.57	Motor converters
.6	Asynchronous machines
.61	Theory
.62	
.63	Induction generators
.64	Induction motors
.65	Series alternating current motors
.66	Repulsion motors
.67	Frequency converters
.68	Phase converters
.7	Rectifying apparatus
.72	Mechanical rectifiers
.73	Arc rectifiers
.74	Electrolytic rectifiers
.314	Stationary induction apparatus
.1	Theory
.2	General types and description
.3	Transformers
.32	Constant current transformers
.33	Constant potential transformers
.34	Phase changing transformers
.38	Meter transformers
.4	Auto transformers
.5	Potential regulators
.51	Compensator potential regulators
.52	Induction potential regulators
.53	Magneto potential regulators

621.314.6	Reactors or choke coils
.7	Induction coils
.315	Electrostatic apparatus
.3	Condensers
.316	Details of electric machinery, parts
.317	Switchboards and control devices, central station wiring
.1	General
.2	Panels
.22	Generator panels
.23	Motor panels
.24	Feeder panels
.25	Transformer panels
.26	Converter panels
.27	Arc light panels
.28	Accumulator panels
.3	Switches
.31	General
.32	Knife switches
.33	Dial switches
.34	Plug switches
.35	Oil switches
.36	Circuit breakers
.4	Rheostats and control devices
.5	Signal devices
.6	Meters and indicating devices
.7	Barriers and compartments
.8	Protective devices (fuses, etc.)
.318	Manufacturing processes
.319	Transmission of electric energy
	Limited to transmission of current from central to sub-stations (stepdown transformers) and to questions common to all lines.
.1	General
.12	Systems
.122	Direct or continuous current systems
.122.1	2-wire systems
.122.2	3-wire (or Edison) and other
.122.9	Other direct current systems
.123	Alternating current systems
.123.1	Single-phase systems
.123.2	2-phase (or quarter phase) systems
.123.23	3-wire system
.123.24	4-wire system
.123.3	3-phase systems
.123.32	Delta or mesh connections
.123.33	Star or Y connections
.123.9	Other polyphase systems

621.319.125	Composite systems
	Direct and alternating current combined
.2	Lines and conductors
.21	General
	Interaction of parallel lines, heat losses.
.22	Overhead or aerial lines
.222	Systems
.223	Poles: foundations, guys, etc.
.224	Cross arms Pins
.225	Towers
.23	Underground lines
.232	Systems
.233	Conduits
.234	Manholes
.3	Cables and conductors Insulating materials
.32	Uninsulated conductors Bare wire
.33	Insulated conductors Wire and cable
.34	Cables
.37	Insulating materials
	Leakage Influence of chemic composition
.4	Insulators
.8	Protective devices
.82	Line lightning arresters
	For protection of central stations see 621.317.8
.32	Electric lighting
.321	Illumination
.1	General
.2	Interior illumination
.21	Domestic
.22	Large halls
.23	Theatre
.24	Shops, warehouses, drafting rooms, etc.
.3	Exterior illumination
.32	Streets
.33	Parks and open places
.4	Decorative illumination
.44	Electric signs
.325	Arc lighting
.1	General
.2	Continuous current open
.3	Continuous current enclosed
.4	Alternating current open
.5	Alternating current enclosed
.6	Flaming arc
.7	Search lights, etc.
.326	Incandescent lighting

621.326.1	General: efficiency, cost, etc.
.2	Systems
.3	Carbon filament lamps
.31	Metalized filament
.32	Other carbon filaments
.4	Metal filament lamps
.41	Platinum filaments
.42	Tantalum filaments
.43	Tungsten filaments
.44	Osmium filaments
.45	Other metal filaments
.5	Glowers of other materials
.53	Nernst lamps
.327	Incandescent vapor lighting and lamps Other electric lighting
.3	Vacuum or incandescent vapor lamps
.4	Mercury vapor lamps
.5	Carbon vapor lamps Moore lamp
.7	Vacuum lamps for special radiations: Crookes tubes, etc.
.328	Apparatus at service end of line
.1	Underwriters' requirements National electric code
.2	House wiring
.3	Panels
.4	Fuses
.5	Insulators, etc.
.6	Meters
.7	Switches
.8	
.9	Other apparatus

.33 Electric traction

.331	General
.2	Systems
.3	Systems according to service
.32	Trunk lines
.33	Interurban
.34	Local
.342	Surface
.343	Elevated
.344	Subway
.4	Systems according to current
.42	Direct current
.43	Alternating current
.431	Single-phase
.432	2-phase

621.331.433 3-phase
.439 Others
.5 Systems according to delivery of power
.52 Trolley systems
.53 Overhead trolley
.54 Underground trolley
.56 Third rail systems
.562 Unprotected third rail
.564 Protected third rail
.332 The line (including track)
.1 General
.17 Feeders and return systems
.2 Overhead wire Trolley lines
.23 Catenary suspension
.25 Trackless trolley
.3 Third rail
.5 Underground conductor or contact
.6
.7 Accessories
.9 Other types of line
.333 Track
.1 General
.16 Deteriorating influences
.167 Electrolysis Leakage
.2 Rails
.4 Bonding
.334 Rolling stock
.2 Locomotives
.3 Motor cars
.4 Accessories and parts Control systems
Motor, controller, current collecting devices, etc.
Multiple unit control
.5 Locomotive and car wiring
.7 Running gear and other non-electric details

.35 Chemic electricity Voltaic cells and generators Primary and secondary

.351 General
E.m.f., counter e.m.f., polarization, weight, capacity; efficiency, life, crumbling, deterioration and detrimental influences; residues
.352 Parts and accessories of cells and accumulators
.1 Containers: jars, troughs, vats, etc.
.2 Electrodes and their accessories: positive and negative plates or elements. Grids, supporting frames, insulating rods, etc.

621.352.3 Diaphragms and partitions
.4 Electrolytes Depolarizers Packing
.5 Circulators Conduits and piping
.6 Connections Terminals Binding posts
.7 Regulating apparatus
.8
.9 Other apparatus
.353 Primary cells
See also 537.5 Voltaic electricity; 541.37 Electrochemistry
.1 General
.3 Single fluid
.4 Double fluid Heavy current cells
.5 Open circuit or non-depolarized
.6 Closed circuit or depolarized
.7 Accessories and parts
.8 Classification according to use or operating methods
.354 Accumulators or storage batteries
Secondary cells and batteries
.1 General
.18 Care and handling of accumulators
.2 Construction of
.3 Operation of
.4 Application of
.7 Accessories and parts

.355 Lead accumulators
.1 General
.18 Care and handling
.2 Naturally formed: Planté type
.3 Artificially formed: Faure type
.4 Combined Planté-Faure types
.5 Other lead accumulators
.52 Complex oxid types
.55 Lead element accumulators
.56 Copper lead accumulators
.57 Zinc lead accumulators
.58 Cadmium lead accumulators
.356 Alkaline accumulators
.357 Other types of accumulators
Thalium, gas, etc.

.37 Electric measurements, meters and testing

.371 General
.372 Standards Calibration of instruments
.373 Meters General types
Recording meters See also special meters, 621.384 prepayment meters
.374 Special meters and measurements
.2 Resistance meters: inductance, capacity
Wheatstone bridges, ohmmeters, resistance boxes

621.374.3 Potential meters: voltage
voltmeters, electrometers, standard cells
.4 Intensity meters: current
Galvanometers, ammeters, coulometers, Ampére-hour meters
.5 Quantity or work meters Watt-hour meters
.6 Power meters Watt meters
.7 Frequency meters Oscillographs
.9 Other meters and measurements
.91 Phase meters Power-factor meters Synchronizers
.379 Other electric measuring instruments
For other than electric measurements: e. g., electric thermometers

WEAK CURRENT ENGINEERING

.38 Electric communication: telegraphy, telephony, wireless For overhead or underground lines, see 621.3192
.381 General
.382 Telegraphy Systems
.15 Codes
.152 Morse
.153 Continental
.154 Phillips (press code)
.2 A B C, dial, needle telegraph, etc.
.21 Early experimental forms
.22 A B C
.23 Dial
.24 Needle
.25 Pointer
.29 Other
.3 Hand operated code telegraphy
.31 Simplex
.311 Open circuit
.312 Closed circuit
.32 Duplex
.321 Differential duplex systems
.322 Stearns duplex
.323 Polar duplex
.325 Bridge duplex systems
.34 Quadruplex
.35 Multiplex
.36 Synchronous multiplex: Delany
.37 Harmonic multiplex: Gray
.4 Automatic code telegraphy High speed systems
.41 Electrochemic automatic: Bain, Morse
.44 Ink recording or embossing

621.382.45	Wheatstone
.46	Pollak-Virag
.47	Telepost (Delany)
.5	Printing telegraphy
.51	Tape printing: stock tickers
.53	Other tape printing: Hughes
.55	Page printing: Buckingham, Murray, Baudot
.57	Multiple page printing: Rowland
.6	Writing telegraphy
	Transmitting and recording characters while being written Gray's telautograph
.7	Facsimile telegraphy
.8	Submarine cable telegraphy
.9	Other wire systems
.94	Induction telegraphy: from moving trains, etc.
.95	Combined telegraphy and telephony Phantom circuits
.383	Telegraph instruments
.1	Transmitting: keys, senders. etc.
.2	Intermediate and accessory: relays. repeaters, switches
.21	Relays
.22	Differential relays
.23	Polarized relays
.24	Repeaters, for simplex: Milliken, Ghegan. Toye, etc
.25	Repeaters for duplex or quadruplex
.26	Half repeaters
.27	Switches and distributing apparatus
.28	Protective apparatus
.29	Miscellaneous telegraph accessories
.3	Receiving instruments
	Sounders, recorders, etc. Subdivided, if wished, like 621.3824-8
.384	Wireless electric communication: telegraphy telephony
.1	General
.2	Wireless telegraphy Systems
.21	Spark telegraphy; by free oscillations
.25	Continuous-train telegraphy: by forced oscillations
.3	Instruments
.31	Sending apparatus
.35	Antennae, aerials, and their substitutes
.36	Receiving instruments and apparatus
.4	Applications, adaptations, specific installations
.5	Wireless telephony systems
.6	Apparatus
.61	Sending apparatus
.65	Aerials, etc.

621.384.66	Receiving apparatus
.7	Applications, adaptations, specific installations
.385	Telephony Systems
.1	
.2	General
.22	Series
.23	Bridging
.24	Selective
.3	Intercommunicating systems
	Without central switchboard
.32	Common return systems; selective at each station
.34	Radial common return systems; selective at one station only
.36	2-wire systems; separate returns
.4	Central switchboard systems
	Manual
.42	Local battery or magneto systems
.46	Common battery or central energy systems
.5	Multiple switchboard systems
.6	Trunking Transfer systems
.61	Trunking
.63	Transfer systems
.7	Semiautomatic and automatic systems
.72	Semiautomatic
.75	Automatic
.76	Strowger system (Automatic Electric Co.)
.8	Private exchanges
.386	Telephone instruments
	Terminal; subscriber's instruments
.2	Transmitters
.3	Receivers
.4	Induction coils
.5	Condensers
.6	Hook or other switches
.7	Call receiving apparatus
.8	Call sending apparatus
.9	Miscellaneous accessories
.92	Coin collecting devices
.94	Protective devices
.96	Current supply (local batteries)
.387	Central switchboards and other station equipment
.1	General
.2	Switchboards, manual
.22	Local battery or magneto
.26	Common battery
.3	Multiple switchboards
.35	Divided multiple

621.387.4 Trunks Transfer boards
.41 Trunks and trunking
.43 A boards
.45 B boards
.47 Multiple plug transfer
.5 Switchboard parts and accessories
.6 Power plant equipment and accessories
.62 Accumulators
.63 Charging generators
.64 Ringing
.7 Automatic and semiautomatic switchboards
Including accessories Subdivided like 621.3857
.8 Telephone transmission
.81
.82 Long distance
.83 Transposition
.84 Telephone cable construction
.85 Loading
.86 Pupin coils
.9 Other central station accessories
.92 Distributing frames and racks; main
.93 Distributing frames and racks; intermediate or secondary
.94 Protective devices
.96 Meters and counters
See also 621.3286 Electric light meters
.389 Other electric communication

.39 Other application of electricity

.4 Air and Gas Engines and other motors

.41 Hot air engines

.42 Compressed (or rarefied) air engines

.43 Internal combustion engines

.431 General theory of internal combustion engines
.2 Thermodynamics of internal combustion
.3 Mechanics Balancing, etc.
.432 Cycles and systems of operation
.1 Four-cycle systems
1, explosion motors 2, constant pressure burning
.2 Two-cycle systems
1, explosion type 2, constant pressure type
.3 Modified cycles or systems
.433 Gas turbines
.434 Internal combustion engines (or engine plants) classified according to fuels

621.434.1 Engines (or plants) for gaseous fuels
.11 Natural gas
.12 Illuminating gas
.13 Blast furnace gas
.14 Producer gas
For gas producers see 665.8
.15 Acetylene gas
.2 Engines (or plants) for liquid fuels
.21 Gasoline
.22 Kerosene
.23 Other petroleum oils
.24 Alcohol
.3 Engines for solid fuels
.436 Special engines or motors
.437 Parts and accessories of internal combustion engines
1, Reciprocating parts; 2, Shafts, Journals and Bearings; 3, Fly-wheels; 4, Governors; 5, Valves and valve gears; 6, Carburetors and mixing valves; 7, Ignition Systems; 8, Oils and other accessories.
.438 Special applications
.3 Self-propelled machinery Farm machinery, road rollers, etc.
.4 Self-propelled vehicles
.5 Motors for small boats
.6 Internal combustion engines in marine service
.7 Airship motors

.44 Binary vapor engines
.45 Windmills
.46 Animal motors Tread mills
.47 Solar engines
.48
.49

.5 Air compression Ice machines Refrigerators

.51 Air compressors
.515 Dry air compressors
.517 Wet air compressors

.53 Compressed air transmission and distribution
.531 General
.532 Details of transmission Piping, mains, gages, etc. Designs of transmissions
.533 Records of tests on air compressors and transmissions
.534 Theory of air compression (thermodynamics of) Loss of pressure in pipes, etc. Efficiency of compressors; Reheating, etc.

621.54 Application of compressed air
.541 Air motors
.542 Pneumatic tools; drills, hammers, etc.
.543
.544 Special applications in railroad service
.545 Compressed air locomotives
.546 Pumping by compressed air
.549 Miscellaneous applications

.55 Rarefied air and vacuum appliances (Vacuum cleaner, etc.)
.56 Refrigerators
.564 Refrigerating fluids
.565 Refrigerating systems and plants
.1 Brine system
.2 Direct expansion system
.566 Design of refrigerating systems Calculation of piping, refrigerating surface, etc.

.57 Refrigerating machines
.572 Ammonia compression machines
.573 Ammonia absorption machines
.574 Carbonic acid machines
.575 Miscellaneous types: Air machines, vacuum machines, etc.

.58 Ice making
.581 Can system
.582 Plate system

.6 Blowing and pumping engines

.61 Piston blowers Blast furnace blowing engines, etc.
.62 Rotary blowers
.63 Centrifugal blowers
.64 Steam pumps and pumping engines
.641 General theory Design and construction
.642 Tests of pumps and pumping engines

.65 Direct-acting pumps
.66 Rotary pumps
.67 Centrifugal pumps
.68 Fire engines
.69 Other blowing and pumping devices

621.7	**Manufactories Engineering works** (See also 670)	
.701	Location, shipping facilities, etc.	
.702	Arrangements of shops Shop buildings	
.703		
.704	Organization and administration	
.705	Employees Wages and salaries Payment of labor (Conveniences for workmen; hours of work; piece work; premium plan; profit-sharing; labor unions; strikes and lockouts)	
.706	Accounting Cost-keeping Estimates	
.707		
.708		
.709		
.71	Drafting room	
.711		
.712	Arrangement	
.713	Equipment Desks, drawing boards, etc.	
.714	Materials and supplies	
.715	Methods and processes employed in making drawings	
.716	Blue-printing processes	
.717	Classification and storage of drawings	
.719	Miscellaneous	
.72	Woodworking shop Pattern shop	
.721	Arrangement of shop	
.722	Equipment	
.723	Woodworking methods and processes	
.724	Pattern making	
.725		
.726		
.727	Preservation and storage of patterns	
.728	Materials and supplies	
.729	Miscellaneous	
.73	Forge shop	
.731	Arrangement of forge shop	
.732	Equipment Forges, blowers, anvils, etc.	
.733	Forging processes	
.734	Drop forging	
.735		
.736		
.737		
738	Materials Supplies	
.739	Miscellaneous	
.74	Foundry	
.740	Generalities (.740.5 Periodicals .740.6 Societies; .740.9 Historical)	

621.741	General arrangement of foundry
.742	Equipment of foundry
.743	Molding processes Green sand, dry sand, loam, etc.
.744	Machine molding
.745	Cupola practice Mixtures of iron Chemistry of foundry irons
.746	
.747	
.748	Materials and supplies
.749	Miscellaneous
.75	Machine shop
.750	Generalities
.751	Arrangement of machine shop Location of shafting and machines
.752	Equipment (752.1 Machine tools; 752.2 Small tools)
.753	Machine work Methods and processes
.754	Bench work
.755	Erecting
.756	Toolmaking Construction of dies, jigs, etc.
.757	
.758	Supplies Materials and stock
.759	Miscellaneous
.76	Blast furnace
.77	Rolling and drawing mills
.78	
.79	Other shops and departments
.792	Boiler and sheet metal shops
.794	Special process shops Galvanizing, plating, etc.
.795	Finishing shop
.796	Storehouses
.8	**Millwork and machinery of transmission Design of machine parts**
.81	Principles of mechanism
.82	Journals, shafting, etc.
.821	Journals
.822	Bearings Ball and roller bearings Bearing metals
.823	Shop shafting
.824	Engine and propeller shafts
.825	Clutches and couplings Friction clutches
.826	Brakes

621.83	Toothed wheels and cams
.831	Forms of teeth; tooth curves; general theory
.832	Efficiency of gears Tests Friction of gears
.833	Design of gears
.1	Spur gears
.2	Bevel and skew bevel gears
.3	Worm and spiral gears
.834	Construction: cutting and casting of gears
.835	Chain gearing
.837	Ratchet gearing
.838	Cams
.84	Valve motions and gears
.85	Machinery and mill gearing
.852	Belt gearing
.853	Hemp rope transmission
.854	Wire rope transmission
.858	Friction gearing
.86	Hoisting and conveying machinery
.862	Hoists
.863	Blocks, tackle, etc.
.864	Winches Capstans Windlasses
.865	Power shovels
.866	Dredges
.867	Conveyors Telferage
.4	Belt or bucket conveyors
.868	Telfers
.87	Cranes and elevators
.872	Derricks
.873	Revolving cranes
.874	Travelling cranes
.875	Locomotive cranes
.88	Fastenings
.882	Screws and bolts Systems of screw threads Screws for transmitting motion
.883	Keys and cotters
.884	Rivets Design of riveted joints
.89	Lubricants Friction
.9	**Machine tools**
.90	Generalities
.901	Design of machine tools
.902	Power required to drive machine tools

621.91 Planing and milling machines
.912 Metal planers, shapers, and slotters
.913 Wood planing machinery

.92 Grinding and filing
.922 Cylinder and surface grinding machines
(Lapping machines)
.923 Emery wheels
.924 Filing machines

.93 Cutting and sawing
.932 Metal sawing and cutting machinery
.933 Wood sawing machinery

.94 Turning
.942 Metal turning lathes
.943 Wood turning lathes
.944 Pipe threading machines
.945 Boring mills

.95 Perforating machinery Drills
.952 Drilling machinery
.953 Wood boring machinery
.954 Reamers
.955 Tapping machines

.96 Punching and shearing machinery
.97 Hammers Nail and rivet machinery
.98 Bending, straightening, and shaping
.982 Bending machinery
.983 Straightening machinery
.984 Flanging and die press machinery

.99 Screw machines Bolt and nut machinery, etc.

622 Mining Engineering

.1 Exploration and Prospecting

.11 Theory, applied geology, etc.
.12 Prospecting
.121 Surface indications
.122 Prospect trenches, shafts and tunnels See 622.2
.123 Booming and other washing methods
.124 Boring methods See 622.24
.129 Unreliable methods, including divining rods, fortune tellers, etc.

622.13 Surface surveying
.131 Surveying mineral claims
.132 Topographical surveying
.133 Geological surveying

.14 Mining surveying
.15 Magnetic surveying
.16 Faults See 551.87 and 553.19
.17 Models
.18 Examination of mineral properties
.181 Principles
.182 Sampling
.183 Estimation of quantity of mineral
.184 Valuation

.19 Mining prospectuses See 553

.2 Practical Mining

.21 Excavation of loose ground See 622.32
.211 Pick and shovel
.212 Plow and scraper
.213 Cableways and grab buckets
.214 Mechanical shovels
.215 Water
.216 Dredges

.22 Quarrying dimension stone
.221 Plug and feathers
.222 Broaches
.223 Channelers
.224 Blasting systems

.23 Breaking solid ground
.231 Fire-setting
.232 Thawing
.233 Undercutting
.1 Hand undercutting
.2 Machine undercutting
.21 Punchers
.22 Cutters
.221 Chain machines
.222 Disk machines
.223 Cutter-bar machines
.234 Wedging without drill holes
.235 Drilling See 622.24

622.235.1 Hand drilling
.11 Churn drills
.12 Hammer drills
.13 Auger drills
.2 Machine drilling
.21 Piston drills
.22 Air hammer drills
.23 Auger drills
.236 Breaking from drill holes without explosives
.1 Wedges
.2 Freezing water
.3 Wetting wooden plugs
.4 Compressed air cartridges
.5 Hydraulic cartridges and direct hydraulic pressure
.6 Lime cartridges
.237 Explosives
.1 Theory
.2 Low explosives
.3 High explosives
.4 Permissible explosives
.8 Testing
.9 Handling and storage See 622.932
.238 Blasting
.1 Theory
.2 Methods
.3 Loading
.4 Firing
.9 Testing blasting appliances

.24 Boring See 622.124, 622.235 and 622.523
.241 Hand boring
.1 Churn borers Spring poles
.2 Rotary borers
.21 Augers
.22 Diamond drills
.23 Shot drills
.242 Machine boring
.1 Churn borers
.11 Cable drills
.12 Rod drills
.13 Hollow rod drills
.131 Suction
.132 Jettings
.2 Rotary borers
.21 Non-coring drills
.211 Straight bit drills
.212 Auger drills

622.242.22 Core drills
.221 Serrated ring drills
.222 Diamond drills
.223 Shot drills

.25 Shaft sinking See 622.122 and 622.552
.251 Plant
.252 Sinking through firm earth
.253 Forepoling
.254 Sinking open caissons
.255 Shield methods
.256 Pneumatic methods
.257 Freezing methods
.258 Boring methods
.259 Drilling and blasting methods

.26 Tunnelling and drifting See 622.122 and 622.524
.261 Plant
.262 Preliminary operations
.263 Forepoling
.264 Forcing forward metal linings
.265 Shield methods
.266 Pneumatic methods
.267 Boring methods
.268 Drilling and blasting methods

.27 Stoping See 622.34
.28 Supporting ground
.281 Timber
.282 Iron and steel
.283 Masonry
.284 Concrete

.29

.3 Working of mines Exploitation

.31 Open workings
.311 Open cut working
.312 Stripping
.313 Milling

.32 Placer workings See 622.21
.321 Small scale working with pan, cradle and long tom
.322 Sluicing
.323 Hydraulicking
.324 Dredging
.325 Cableway methods

622.326 Mechanical shovel methods
.327 Dry placer methods

.33 Methods used mainly in coal mining
.331 Longwall methods
.332 Room and pillar methods, including panel method

.34 Methods used mainly in metal mining
.341 Overhand stoping
.342 Underhand stoping

.35 Working thick deposits
.351 Caving method
.352 Filling method
.353 Square set method
.354 Square work method

.36 Working soluble deposits
.361 Salt
.362 Copper sulphate

.37 Working fusible deposits
.371 Sulphur

.38 Working liquid and gaseous deposits
.381 Water
.382 Petroleum
.383 Natural gas
.384 Volcanic emanations

.39

.4 Ventilation, lighting and signaling

.41 Theory of ventilation
.411 Mine atmospheres
.1 Gases See 622.811
.2 Dust See 622.812
.3 Humidity
.4 Temperature
.412 Resistance to circulation of air
.413 Splitting currents of air

.42 Natural ventilation
.43 Mechanical ventilation without fans or blowers
.431 Cowls
.432 Furnaces
.433 Steam jets
.434 Waterfalls

622.44 Fans and blowers See 623.95
.441 Fans
.1 Disk fans
.2 Centrifugal fans See 621.63
.442 Blowers
.1 Rotary blowers See 621.62
.2 Piston blowers See 621.61

.45 Airways, stoppings, regulators
.46 Lighting, safety lamps, etc. See 622.975
.48 Signaling

.5 Drainage

.51 Theory of infiltration of water
.511 Surface water
.512 Ground water
.513 Deep water

.52 Drainage without raising water
.521 Natural drainage
.522 Gutters
.523 Bore holes See 622.24
.524 Tunnels See 622.26

.53 Pumps actuated by surface motors
.531 Rod lift pumps
.1 For mines
.2 For deep wells
.532 Cornish pumps
.533 Bull pumps

.54 Pumps actuated by underground motors
.541 Reciprocating pumps
.1 Station pumps
.11 Steam
.12 Air
.13 Electric
.14 Hydraulic
.2 Sinking pumps
.21 Steam
.22 Air
.23 Electric
.542 Centrifugal pumps
.1 Station
.2 Sinking
.543 Direct displacement pumps

622.543.1 Steam
.11 Pulsometers
.12 Steam jets
.2 Air
.21 Exhausting air-pressure pumps
.22 Return-air pumps
.23 Air lifts

.55 Hoisting of water See 622.65 and 622.67
.551 Water buckets and tanks
.552 Water shafts See 622.25

.56 Dams and water tight linings See 622.254 and 622.264
.57 Handling special waters
.571 Acid waters
.572 Hot waters

.58 Hand pumps
.59 Siphons

.6 Extraction, hoisting and transportation

.61 Handling mineral in working place
.611 By hand
.612 By machine

.62 Underground roads
.63 Cars, trams, etc.
.64 Transportation by gravity
.641 Chutes
.642 Batteries
.643 Gravity planes
.644 Retarding conveyors

.65 Haulage and hoisting by men and beasts
.651 Haulage
.1 Wheeling in barrows
.2 Tramming
.3 Animal haulage
.652 Hoisting
.1 Windlasses
.2 Whims

.66 Mechanical haulage
.661 Rope haulage See 622.673 and 622.674
.1 Theory
.2 Haulage engines

622.661.3	Engine planes
.4	Endless-rope haulage
.5	Tail-rope haulage
.662	Locomotive haulage
.1	Theory
.2	Steam locomotives
.3	Compressed air locomotives
.4	Oil locomotives
.5	Electric locomotives
.67	Mechanical hoisting
.671	Theory
.672	Hoisting engines
.1	Steam hoists
.2	Compressed air hoists
.3	Oil hoists
.4	Electric hoists
.673	Drums, reels, clutches and brakes
.674	Ropes and chains
.1	Manila ropes
.2	Wire ropes
.3	Chains
.675	Head frames
.1	Timber
.2	Steel
.676	Hoisting systems
.1	Unbalanced hoisting
.2	Balanced hoisting
.3	Koepe system
.4	Whiting system
.68	Cages, skips, buckets, slope carriages
.69	Surface transportation including mineral roads, wire ropeways, transhipment, loading and unloading. (See 622.99)
.691	Wagon roads
.692	Railways
.693	Aerial tramways
.694	Telphers
.698	Loaders
.699	Unloaders, dumps, etc.
.7	**Mechanical preparation Ore dressing**
.71	Theory Preliminary operations
.72	Hand dressing See 622.781

622.73 Crushing See 622.782
.731 Theory
.732 Hand breaking
.733 Mechanical breaking
.1 Jaw breakers
.2 Spindle breakers
.734 Crushing
.1 Rolls
.2 Roller mills
.3 Stamps
.4 Impact pulverizers
.5 Ball mills and tube mills
.6 Arrastras and grinding pans

.74 Screening See 622.783
.741 Theory
.742 Perforated metal and wire cloth
.743 Grizzlies
.744 Shaking screens
.745 Pulsating screens
.746 Trommels
.747 Belt screens

.75 Wet concentrating machines Ore concentrators
See 622.77 and 622.784
.751 Theory
.752 Disintegrators
.1 Trough washers
.2 Log washers
.3 Wash trommels
.4 Washing pans
.753 Hydraulic classifiers
.1 Free-settling classifiers
.11 Carrying-current classifiers
.111 Buddles
.112 Riffles, canvas tables, etc.
.113 Box classifiers
.114 Settling boxes and ponds
.12 Hydraulic-current classifiers
.121 Trough
.122 Pocket
.123 Tubular
.2 Hindered-settling classifiers
.21 Wolf-tongue classifiers
.22 Pulsator classifiers
.754 Jigs
.1 Hand

622.754.2	Power
.21	Pan
.22	Piston
.23	Pulsator
.755	Tables
.1	Agitation sizing tables
.11	Bumping
.12	Jerking
.2	Film sizing tables
.21	Fixed
.22	Moving
.756	Vanners
.1	Side-shake
.2	End-shake
.76	**Slime treatment** See 622.75
.77	**Concentration by other means than wet concentration**
.771	Pneumatic concentration See 682.785
.772	Oil concentration
.773	Flotation
.774	Magnetic separation
.775	Electrosctatic separation
.776	Disintegration and screening See 622.78
.78	**Preparation of coal** See 622.71
.781	Picking See 622.72
.1	Hand
.2	Mechanical
.782	Crushing See 622.73
.1	Jaw breakers
.11	Sauerman
.12	Roll and jaw
.2	Rotary crushers
.3	Rolls
.31	Toothed
.32	Corrugated
.33	Smooth
.4	Impact pulverizers
.41	Hammer
.42	Disintegrator
.783	Screening See 622.74
.1	Trade sizes
.2	Bar screens
.3	Shaking screens
.4	Revolving screens
.784	Washing See 622.75

622.784.1 Hyraulic classifiers
.11 Carrying-current classifiers
.111 Grading boxes
.112 Trough washers
.12 Hydraulic-current classifiers Tub washers
.2 Jigs
.21 Pan
.22 Piston
.23 Compartment
.3 Tables
.32 Bumping
.33 Jerking
.785 Pneumatic concentration See 622.771
.786 Concentration by crushing and screening Bradford pulverizers See 622.776
.787 Coking See 644.22, 622.7 and 669.8
.1 Theory
.2 Open pits
.3 Beehive ovens
.4 Longitudinal ovens
.5 Gas retorts
.6 By-product ovens
.788 Briquetting
.1 Peat
.2 Lignite
.3 Bituminous coal
.4 Anthracite
.5 Coke
.789 Coal preparation plants See 622.79
.1 Tipples
.2 Breakers
.3 Washeries
.4 Coking plants
.5 Briquetting plants

.79 Mineral preparation plants See 622.789
.791 Rock houses, shaft houses
.792 Patios
.793 Concentrating mills

622.8 Dangers and accidents

.81 Explosions, see 622.82
.811 Marsh gas explosions
.1 Theory
.2 Causes
.3 Actual cases
.4 Preventive measures
.812 Coal dust explosions

622.812.1	Theory
.2	Causes
.3	Actual cases
.4	Preventive measures
.82	Mine fires See 622.81
.821	Timber fires
.1	Theory
.2	Causes
.3	Actual cases
.4	Methods of extinguishment
.5	Preventive measures
.822	Gob fires
.1	Theory
.2	Causes
.3	Actual cases
.4	Methods of extinguishing
.5	Preventive measures
.823	Fires in coal
.1	Theory
.2	Causes
.3	Actual cases
.4	Method of extinguishment
.5	Preventive measures
.824	Fires in sulphide ore
.1	Theory
.2	Causes
.3	Actual cases
.4	Methods of extinguishment
.5	Preventive measures
.83	Crushing and falls of ground
.84	Flooding of mines
.85	Accidents to miners
.851	Accidents due to falls of ground See 622.83
.852	Accidents due to explosives and blasting
.853	Haulage accidents
.854	Hoisting accidents
.855	Accidents due to machinery
.856	Electric shocks
.857	Falling down shafts, chutes, etc.
.858	Accidents due to explosions and fires See 622.81 and 622.82
.859	Miscellaneous accidents
.86	Rescue and relief
.861	Mine rescue
.1	Apparatus
.2	Systems

622.861	
.3	Actual cases
.862	First aid
.1	Outfits
.2	Methods
.3	First aid teams
.867	Doctors
.868	Hospitals See 622 975
.869	Miners' insurance and compensation
.87	Sicknesses of miners
.9	**Surface plants** See 622.789 and 622.79
.91	Offices
.911	General offices
.912	Mine offices
.92	Storehouses and yards
.921	General storehouses
.922	Powder houses
.923	Tool houses
.924	Oil houses
.925	Lamp houses
.936	Yards for lumber and other combustibles
.937	Yards for steel and other non-combustibles
.93	Shops
.931	Blacksmith shops
.932	Machine shops and foundries
.933	Carpenter shops and sawmills
.94	Power plants
.941	Steam plants
.942	Compressed air plants
.943	Electric plants
.95	Fan houses
.96	Stables
.97	Buildings for employees
.971	Change houses, wash houses, dry houses, shift houses
.972	Club houses
.973	Dwellings
.974	Stores
.975	Hospitals

622.98 Fire protection

.99 Arrangement of surface plants See 622.69

623 Military and Naval Engineering

.8 Naval architecture

624 Bridge engineering Arches

Construction in wood, stone, and metal

This classification includes whatever concerns the methods and principles of construction, so that the computations and technical conditions may be established, or the way the movable parts act on each other For architectural features see 720, Architecture

624.0 General

Subdivisions of 624.0 may be combined with the following subdivisions, 624.1—624.9, for specifying details of construction under consideration

.01 Classification of bridges according to the character of the material used

.011 Wooden bridges

(1 Wooden pile bridges; 2 bridges on stone piers; 3 bridges covered with iron)

.012 Masonry bridges

(1 Stone bridges; 2 brick bridges; 3 bridges of concrete, plain and reinforced)

.013 Metal bridges on stone piers

(1 Cast iron bridges; 2 iron and steel bridges)

.014 Bridges entirely of metal

(1 Bridges of cast iron; 2 bridges of iron and steel)

.02 Classification of bridges according to purpose

.021 Bridge sidewalks for foot passengers

.022 Road bridges

(1 Carriage bridges; 2 railway bridges; 3 bridges with more than one track; 4 bridges with more than one story)

.023 Viaducts

.024 Canal and aqueduct bridges

.025 Tunnel bridges

.026 Sluice and toll bridges

.027 Movable and turning bridges

.028 Military and temporary bridges

(1 Wooden emergency bridges; 2 trestle bridges; 3 pontoon bridges; 4 portable metallic bridges)

.03 Classification of bridges according to outline or type

624.031 Right bridges
.032 Skew bridges
.033 Curved bridges
.034 Single span bridges
.035 Bridges of multiple independent spans
.036 Bridges of continuous spans

.04 Determination and computation of component parts of bridges
See also 620.1—Resistance of materials
.041 Establishment of the general outline Working drawing
.042 Computation of loads, dead and alive
Permanent loads, accidental loads, trial loads, wind loads, temperature stresses
.043 Computation of the dimensions
.1 Dimensions of arches
(11 Curve of pressure; 12 diagram of stability)
.2 Dimensions of timber work
(21 Main timbers; 22 accessory members; 23 wind bracing)
.3 Dimensions of piles and abutments
.044 Computation of deformation Flexure, curve of deforation
.045 Computation of weight and cost
(1 Weight of Parts; 2 net price)

.05 General conditions of location Methods of construction
.051 Determination of site Study of soil
.052 Location of approaches
.053 Choice of type Fixing the principal dimensions Height Width
.054 Determination of the waterway Estimating the flow Computation of eddies
.055 Organization of work yards Excavation and removals
.056 Preparation of component parts Assemblage Stone cutting
.057 Erecting, scaffolds, launching
.058 Trials, tests

.06 Masonry vaults and arches Various types
.061 Names according to rise or direction Right arches Skew arches Descending arches Full centered arches Flat arches Ascending arches
.062 Cylindrical arches Vaulted arches Names according to profile Circuean arches Basket handled or oval arches Elliptical or parabolic arches Pointed arches

624.063 Penetrating arches Vaulted arches with lunettes Grom arches cloistered arches Cloistered arches with plastered covering

.064 Ring arches, vaulted or descending

.065 Spherical vaults Simple domes Domes of cupola lights Partly cylindrical niches Overhanging arches Back-covering

.07 Constituent parts Methods of construction

.071 Intrados, Estrados, Soffit, Spandell

.072 Voussoir, or keystone Height or rise Keys Counter keys Bed joints Rising joints Bearings or springers

.073 Supports Upright pillars or props Drums Pendentives

.074 Construction of arches, centering and scaffolding Masonry work Dressing and laying stone Striking the centers Complementary work Coping Spandrel Filling up

.075 Computation and diagrams of arches

.1 Computation of weight and loads

.2 Diagrams of arches

(21 Curve of the intrados; 21 depth of the keystone)

.3 Thickness of piers

.4 Equilibrium polygon

.5 Weight diagram

.6 Computation of weights

.08 Trussed girders Component parts and computations

.081 Parts of trusses in ordinary wood Principal rafters, ties, struts, tie-beams, braces False tie-beams Hammer beams Purlins Brackets Wallplates Ridge-pole Luths

.082 Special parts of trusses of jointed wood, curved, or of great span

.083 Parts of metal trusses

.084 Parts of composite trusses

.085 Computation of loads and reactions

.086 Computation of dimensions of parts

.087 Computation of weight

.1 Piers and abutments Foundation work

.11 Foundations Generalities Nature of the soil See also 721.1, Foundations in general

.111 Dry foundations

.112 Foundations by draining

624.113 Sunk concrete Cribs and frame foundations in general
.114 Foundations on piling
.1 In river beds Platforms and open caissons
.2 Foundations in soft earth
.3 Metal piers
.115 Foundations by compressed air
.1 Tubular caisson foundation in river beds
.2 Foundations in ground
.3 Movable caissons Montaigue system

.12 Abutments
.121 Abutments for wooden bridges
.122 Abutments for masonry bridges
.1 Dressing the abutments
.2 Abutments of loose stones
.3 Wing walls Curved walls
.4 Hollow abutments
.123 Abutments of metal bridges

.13 Wooden piles Stakes
.14 Masonry piles
.141 Piles of uniform strength
.142 Cut-waters
.143 Preparation of the piles
.144 Hollow piles
.145 Piles for floors Piles for bridges

.15 Metal piles
.151 With four uprights
.152 With more than four uprights
.153 Piles of uniform strength

.2 Beams Floors of bridges Shapes and arrangement

.21 Wooden bridges
.211 Primitive arrangements Simple beams Without beams Spurs
.212 Floors of beams
.213 Trussed beams and spliced beams For arch bridges see 624.61
.214 American lattice bridges Towne's system
.215 American like St. Andrews cross Howe system

.22 Bridges of metal construction Iron and steel beams American trusses
.221 Simple metal trusses
.1 Trusses with rigid joints
.2 Trusses with solid core

624.221.3 Lattice trusses
.4 Side pieces and crosses of St. Andrew
.222 Trusses of concrete and reinforced concrete
.223 American trusses with jointed connections
.1 Simple American trusses
(11 The Warren triangular system; 12 the Howe system; 13 the Pratt and Whipple systems; 14 protected trusses)
.2 Composite American trusses
(21 Warren multiple system; 22 Linville system; 23 Poat system; 24 the Bollman system)
.3 Compound American truss
(31 The Warren system; 32 the Pratt or Pettit system; 33 the Howe system; 34 the Funk system)

.3 Metal lattice bridges Different kinds

.31 With trusses of constant height Ordinary lattice
.32 With variable height or bowstring
.33 Cantilevers
.34 With joints or crane bridges

.4 Metal tubular bridges

.5 Suspension bridges Different kinds parts

.51 General arrangement Different types
.511 Bridges with flexible hangers
(1 With single panel; 2 with several panels; 3 with auxillary trusses; 4 with stays)
.512 Bridges with rigid hangers
.1 With parabolic cable and straight beams
.2 With cable and parabolic beams
.3 With parabolic cable and horizontal stringers

.52 Suspension chains and cables
.521 Main cables
.522 Reserve cables
.523 Anchorage cables
.524 Suspension chains and rods

.53 Floors
.54 Piers Towers
.55 Abutments Anchorages

.6 Arch bridges Different kinds

.61 Wooden bridges of one or more spans
.62 Masonry bridges of one or more spans
.621 Stone bridges
.622 Brick bridges
.623 Plain and reinforced concrete bridges

624.63 Cast iron bridges on masonry piers, with one or more spans

.64 Bridges entirely of cast iron

.65 Steel and iron bridges on masonry piers

.651 Single span bridges

.652 Independent span bridges

.653 Continuous bridges

.66 Steel and iron bridges on metal piers

.661 Single span bridges

.662 Independent span bridges

.663 Continuous bridges

.67 Bridges with elevated arch

.7 Bridges of composite construction

.71 Bridges of unlike spans in masonry and metal

.72 Bridges and viaducts with superimposed spans

.73 Metal bridges with several types of span

.74 Bridges with floor raised with lifts

.8 Movable and shifting bridges Methods of operation

.81 Draw bridges (pont-levis)

.82 Swing bridges

.83 Bascule bridges

.84 Trunion bridges

.85 Rolling bridges

.86 Bridges shifting in the air

.87 Jack-knife bridges

.88 Agencies for operating movable bridges

.881 Movement by hand

.882 Movement by hydraulic power

.883 Movement by steam

.884 Movement by electricity

.9 Roofs and framing Vaults

Construction adapted to considerable spans

See also 695. coverings and 721.5 dwellings

.91 Types of roofs

.911 Roofs of trusses

.912 Mansard roofs

.913 Roofs of curved beams

624.914 Roofs of great span
(1 With wooden trusses; 2 with metal trusses; 3 with combined wood and metal trusses)

.92 Vaulted edifices of masonry

.921 Buildings of one nave

.922 Buildings with coupled naves Aisles

.93 Buildings of great width in masonry and in metal Public halls, etc.

.94 Buildings entirely of metal Halls Markets Exposition buildings

.95 Various metal construction Scaffolding Towers

625 Railway and road engineering

.1 Railways Roadbed and work of construction

.11 The survey and location

.111 Preliminary studies Plans Special features of drawings (stations, branches, stonework, crossings on a level, tunnels)

.112 Extent of the road

.113 Longitudinal profile Grades Curves

.114 Cross-sections Computation of earthwork

.12 Sub-grade

.121 Acquisition of land

.122 Buildings and consolidating the embankments

.123 Drainage of the foundation bed

.13 Stone work, bridges and tunnels Ventilation of tunnels

.14 The track

.141 Ballast

.142 Supports (ties, etc.)

.1 General principles Longitudinal and tranverse solitary supports Comparison

.2 Supports of wood

.3 Supports of metal

.4 Supports of reinforced concrete

.5 Supports of stone

.143 Rails and rail attachments

.1 Forms of rails Weight of rails

.2 Quality of metal in rails Conditions of manufacture Tests

.3 Wear and breakage of rails

.4 Joints of rails Fish joints

.5 Attachment of rails to supports Creeping

625.144 Laying the track
.1 Width and position of joints Length of rails Spacing the cross bars
.2 Excess gauge and superelevation (bending) Laying track on curves
.3 Splices
.4 Operation of track laying

.15 Equipment of the track
.151 Branches (switches, frogs, switch blocks)
.152 Crossings
.153 Junction-crossings
.154 Turntables and swing bridges
.155 Car rollers or shifters
.156 Various accessory appliances (buffers, cyclometers, etc.)

.16 Secondary installations
.161 Sheds and watchman's houses Section houses
.162 Right-of-way fences and bars at grade crossings Setting land marks
.163 Cultivation and planting
.164 Snow screens
.165 Approaches

.17 Care of the road Maintenance and renewals
.171 Inspection Control
172. Current maintenance Condition of the road Dudley dynamometer Maintaining the joints Dynamometer cars
.173 Repairs and renewals
.174 Clearing away snow
.175 Velocipedes for track inspection
.176 Changing the alignment

.18 Stores Road materials Accounts
.19

.2 Rolling stock (For locomotives, see 621.13)
.205 Periodicals; .206 Societies; (Am. Assn. of Master Car Builders)

.21 Cars and carriages, principal parts of
.211 Frames
.212 Axles Wheels Tires Balancing of wheels
.213 Suspension
.214 Provisions for lubricating Lubricants
.215 Trucks Radial and convergent axles
.216 Couplers and buffers Draft gears

625.22 Cross section of cars Clearance of bridges and tunnels Influence of length of cars on curves

.23 Passenger cars

.23 Types and comparison of types Seating capacity Weight

.231 Compartment cars

.232 Corridor or vestibuled cars Parlor cars Sleeping cars Dining cars, etc.

.233 Lighting of cars

.234 Heating and ventilation of cars Sanitation

.24 Freight cars

.24 Generalities Capacity Weight

.241 Flat cars

.242 Hopper and dumping cars

.243 Closed and covered cars

.244 Refrigerator cars

.245 Special cars Dynamometer cars (See 656.221.7)

.246 Details of construction Use of steel in construction

.247 Carunloaders Miscellaneous unloading and dumping devices

.25 Brakes Hand, automatic, continuous, etc. Air brakes

.26 Car repair shops

.27 Supplies Materials

.3 Inclined and mountain railways

.4 Elevated and underground railways Subways

.5 Cable roads

.6 Tributary railways or feeders Street railways

.61 Tributary railways from a technical standpoint

.611 Traffic; taxes; .612 administration and operation; .613 sub grade; .614 track and track equipment; .615 stations; .616 motive power; .617 rolling stock

.62 Street railways Tramways

.63 Traction systems

.7 Roads and highways Country roads and city streets

.71 Varieties of ordinary roads, according to the importance or purpose

.711 Rural roads, wide or narrow

.712 Town roads

(1 Thoroughfares, avenues, boulevards; 2 narrow streets, alleys; 3 covered ways; 4 squares; 5 promenades and public gardens)

625.72 Surveys and maps of routes
.721 Drafting
.722 Staking out the line
.723 Longitudinal profile
.724 Curve notes
.725 Leveling
.726 Computation of excavation and embankment

.73 Various features of the route Roadbed Cross-sections

(1 Cross-sections; 2 carriage ruts, crowning, inclines; 3 equipment; 4 sidewalks; 5 drains; 6 slopes; 7 retaining walls; 8 parapets)

.74 Method of road construction Construction equipment
.741 General questions
Flag stones Stone pavements Wooden pavements Macadam roads Monolithic roads Cement, asphalt, gavel and earth roads
.742 Equipment earth roads, macadam roads, paved roads
.743 Sidewalks, macadam, paved, flagging, brick, tiling, sandstone, asphalt, wood
.744 Curbing
.745 Accessory construction

(1 Bridges and culverts; 2 aqueducts; 3 manholes; 4 drains; 5 protection stones; 6 mile stones, sign posts; 7 cultivation; 8 lighting, lamp posts; 9 other features)

.75 Construction work
.751 Substructure Embankment Haul Shaping the cross-section
.752 Roadway Work of consolidation
.753 Accessory work

.76 Maintenance of way
.761 Maintenance of paved streets Replacing worn stones
.762 Maintenance of macadam roads
.1 The continuous repair method Closing to travel Excessive sweeping Method of making repairs Use of material, of concrete
.2 Periodical ballasting Various methods
.3 Rolling
.4 Tarring or oiling the road
.763 Maintenance of wooden roads
.764 Maintenance of monolithic or concrete roads
.765 Maintenance of asphalt roads
.766 Maintenance of foot paths
.767 Maintenance of cycle tracks

625.768 Current minor details of maintenance
.1 Sweeping Use of brooms Wheel sweepers
.2 Scraping and removing wash water
.3 Removal of filth
.4 Removal of dead leaves and other debris
.5 Removal of snow Cleaning by salt
.6 Sanding and ice removal
.7 Sprinkling Use of sprinklers, hose, water columns, sprinkling costs
.8 Lighting
.9 Other maintenance work

.77 Planting trees and shrubs along the roads
.771 Conditions to be observed Ways of planting Single, double or multiple rows Spacing the trees
.772 Choice of species Species used
.773 Operation of planting Trenches Transplanting Nurseries
.774 Maintenance and protection of vegetation

.78 Sanitation applied to streets and roads
.79 Other work connected with roads

.8 Paving stone, paving Macadamizing and other methods of consolidating roads

.81 Paving stone
.811 Stones used Different kinds Granite, limestone, marble, etc.
.812 Splitting and dressing paving stone
.813 Puttin· in place

.82 Stone p..vements
.821 Stone used Granite Sandstone Porphyry Other hard stone
.822 Preparing the stone
.823 Making the stone pavement
.1 The sand foundation
.2 Layers of stones Curbs Old pavements
.3 Setting the stone
.4 Crossings

.83 Wooden pavements
.831 Wood used Pine Hardwood
.832 Preparation of the pavement
.833 Making the pavement
Staking out Fixing the profile of the concrete foundations Concrete foundations Laying the pavement

625.84 Concrete roads
.85 Asphalt roads
.86 Stone covered roads
.861 Materials used Crushed stone Limestone Flint Quartz Sandstone, granite Hornblend Porphyry Trap, basalt and lava Waste from potteries
.862 Preparation of materials Crushing the stone Crushing by hammers Crushers Storing
.863 Applying the metal covering
.1 Method of Tressaquet
.2 Macadamizing
.3 Method of Poloncease
.4 Metal on foundations
.5 Metal without foundation
.6 Diagonal waterways Catchbasins
.7 Rolling Rollers, hand, horse, steam
.87 Metallic roads Roads of vitreous stone Roads of reinforced stone
.88 Establishment of side walks, curbing, flagging
.89 Other work connected with paving

.9 **Other means of transportation on land**
.91 Ship railways
.92 Transportation by aerial cables

626 **Canal engineering**

627 **River, harbor and general hydraulic engineering**
.1 Rivers Force of water Discharge Bars
.2 Harbors Breakwaters
.3 Docks, piers and quays Shipping facilities
.4 Dikes and levies Embankments
.5 Other protection and reclamation of land from tides and waves Drainage
.6 Jetties
.7 Dredging Dredging machinery
.8 Dams
.9 Light-houses Buoys

628 **Sanitary engineering Waterworks**

Use same form divisions as under 620

.1 **Water supply of towns** (For isolated water supply see 628 7)

.11 Sources of water supply: lakes, rivers, springs, wells and pumping

.12 Pumping vs. gravitation systems: pump-well, stand-pipe high service Holly system

.13 Storage and service reservoirs

.14 Conduits Aqueducts Tunnels

.15 Mains and service pipes Freezing Iron Lead

.16 Impurities and their removal Filter-basins, etc.

.17 Public (sprinkling, fire, flushing), manufacturing, and domestic use and waste Meters

.2 **Sewerage works**

.21 Sewerage systems

.211 Combined system

.212 Separate system

.213 Liernur system

.214 Shone systems

.215 Berlier system

.216 Other systems

.217 The outfall

.218 Depth and alignment

.219 Grade and velocity

.22 Shape and size of sewers

(1 storm water flow; 2 ordinary flow; 3 circular section; 4 ordinary; egg-shape; 5 other egg-shapes; 6 other forms; 8 formulas for size)

.23 Ventilation of sewers

(1 openings in streets; 2 lamp posts; 3 flues in houses; 4 pipes on houses; 5 house drains; 6 chimneys and furnaces; 7 charcoal and chemicals to deodorize sewerage gas; 8 special mechanism; 9 special construction)

.24 Design and construction of sewers

.25 Sewer appurtenances

(1 junctions; 2 house connections; 3 manholes and lampholes; 4 flushing shafts and fixtures; 5 catch basins and inlets; 6 traps and ventilators; 7 valves and penstocks; 8 overflows and regulators; 9 miscellaneous)

.26 River crossings

.27 Intercepting and outfall sewers

.28 Reservoirs and tank sewers

.29 Pumping stations

628.3	**Disposal of Sewage**
.31	Physical properties of sewage
.32	Deodorization and disinfection of solids and liquids (See 628.237)
.33	Subsidence
.34	Precipitation
	(1 precipitation tanks; 2 mixing machinery; 3 filter presses; 4 precipitation by salts of alumina; 5 by lime; 6 by salts of iron; 7 by other methods; 8 disposal of sludge; 9 miscellaneous)
.35	Filtration
.36	Irrigation
	(1 broad irrigation; 2 ridge and furrow irrigation; 3 flat bed irrigation; 4 sub-suface irrigation; 5 intermittent downward filtration; 6 carriers and appurtenances; 7 drains and drainage on sewage farms; 8 filtration areas; 9 miscellaneous)
.37	Sewage farming Required modifications of ordinary methods
.38	Sewage manures
.39	Discharge into sea, etc.
.4	**Sanitation of towns**
.41	Middens and privies
.42	Pail system
.43	Earth closet systems
.44	Domestic ashes and garbage
.45	Public urinals and latrines
.46	Street cleaning and sprinkling
.47	Pavements and subways
.48	Trees in streets and squares
.49	Manufacture of fertilizers from town waste
628.5	**Industrial sanitation**
.51	Factories and trades
	(1 prevention of dust and fumes; 2 protection of throat and eyes; 3 protection against infection; 9 special trades)
.52	Effluvium nuisances
	(1 situation of works; 2 use of high chimneys; 3 condensation in water; 4 combustion in furnaces; 9 special trades)
.53	Smoke nuisance
	(8 From steam generators; 9 From special industries)
.54	Disposal of solid and liquid wastes
	(1 discharge into streams; 2 absorbing wells and burial; 3 clarification by subsidence; 4 chemical treatment; 5 filtration; 6 purification by the soil; 9 special methods and special trades)

628.6 House drainage

.7 Rural water supply Villages and country houses

.8 Ventilation and heating (See 697, 628.23)

This head is chiefly for ventilation. Most matter on heating goes in 697

.9 Lighting (See 621.32, 537.83)

650 Communication Commerce

651 Office equipment and methods

652 Writing Materials Typewriters

653 Stenography

654 Telegraphy (For telegraph and telephone engineering see 621.38)

.6 Telephones

655 Printing and publishing

656 Transportation Operation of railways

.1 Transportation on roads and highways

.2 Transportation by railways

.21 Railway terminals and stations

.211 Arangement of passenger stations

.212 Arrangement of freight and terminal stations

.213 Stations for special purposes (coal, live stock, etc.)

.214 Union stations Division of expenses

.215 Heating and lighting of stations

.22 Trains

.221 Train resistance

.1 Resistance of freight trains

.2 Resistance of passenger trains

.3 Resitance o fengines

.4 Resistance on electric roads

.5 Resistance of foreign rolling stock

.6 Air resistance

.7 Dynamometer cars (See 625.245)

.222 Running of trains Schedules

.223 Use of and distribution of rolling stock

(1 Passenger cars; 2 Freight cars; Return of empty cars; Interchange of cars)

.224 Passenger train service Postal service

.225 Freight service Making up trains Tonnage rating

.226 Baggage service

656.227 Transportation of dangerous and perishable freight
.228
.229 Military transportation

.23 Traffic and rates
.231 Transportation tolls and rates in general
(Revision of rates Basing rates Differential rates Zone tariffs, etc;)
.232 Cost of transportation
.233 Competition of railways Division of traffic Pools, agreements, etc.
.234 Passenger rates Rates for baggage, dogs, etc. Passes and reduced fares
.235 Freight rates Classification of freight
.236 Rates for transportation other than by railway
Rates of porterage and drayage Steamer rates Street railway rates
.237 Accounting and auditing Supervision of receipts and expenses

.24 Damage Delays Claims Responsibility
.25 Safety appliances
.25 General rules
.251 Signals in general Forms Colors Sounds Daltonism
.252 Hand signals Train signals
.253 Fixed track and station signals
.254 Apparatus for long distance communication Bells and special warning signals Telegraph Telephone Communication between stations and running trains Various operating systems Train dispatching Protection of trains in distress
.255 Staff and ticket system of controlling trains
.256 Block systems
.1 Simple manual block signals
.2 Electrically controlled manual block signals
.3 Automatic electric block signals
.4 Automatic pneumatic block signals
.257 Centralization of operation of switch and signal systems Interlocking switch and signal apparatus Electro-pneumatic interlocking devices
.258 Indirect blocking systems Electric slot Ring and key Locking of draw-bridges
.259 Other safety devices
(Apparatus placed in trains Communication between cars and with locomotive Speed indicators on trains or along the track)

.26 Accessories to railway service Dray and cab service Buffets, restaurants and hotels

656.27 Operation of line with light traffic and of local and tributary railways

.28 Accidents
.280 Statistics General questions
.281 Derailments
.282 Broken couplings Runaway cars
.283 Collisions
.284 Other accidents
.285 Accidents to railway employees
.296 Accidents to the public upon railway property

.29 Miscellaneous questions relative to railway transportation

.3 Transportation by horseless vehicles

.30

.31

.32 Automobiles
.321 Types
.1 Pleasure vehicles
.2 Commercial vehicles
.3 Agricultural vehicles
.322 Motive powers
.1 Internal combustion motors
.2 Steam motors
.3 Electric motors
.323 Principal parts (excluding motors)
(1 frames, springs, etc.; 2 clutches, brakes; 3 gear; 4 axles, differentials; 6 wheels, rims, tires; 7 steering gear; 8 journals)
.324 Design and construction
.325 Testing
.329 Maintenance, operation, laws, etc.

657 Book-keeping Accounting

660 Chemical technology

661 Chemicals
(1 chemical elements; 2 acids; 3 alkalies; 4 salts)

662 Pyrotechnics Explosives

665 Oils Gases

665.2 Animal oils and fats

.3 Vegetable oils and fats

.4 Mineral oils Paraffin Asphaltum

.7 Illuminating gases

.8 Other gases

666 Ceramics Glass, etc.

(1 Glass; 2 Enamel; 3 Ceramics; 4 Clay; 5 Porcelain; 6 Stoneware and earthenware)

666.7 Bricks Tiles

.8 Artificial stone

.9 Cements Limes Mortars

667 Bleaching, dyeing, etc.

668 Other organic chemical industries

669 Metallurgy and assaying

669.1 Iron and steel

.11 Economic factors
.111 Sources
.112 Production
.113 Costs
.114 Prices
.115 Uses

.12 Nature and properties
.121 Composition Analyses
.122 Constitution
.1 Thermal examinations Diagrams
.2 Metallography
.123 Physical properties Tests
.124 Chemical properties Corrosion

.13 Alloys
.131 Nickel
.132 Manganese
133 Chrome
.134 Tungsten
.135 Molybdenum
.136 Vanadium

669.137	Silicon
.138	Titanium
.139	Other alloys
.14	**Extraction**
.141	Direct processes
.142	Blast furnace process
.143	Electric furnace process
.15	**Purification**
.151	Puddling processes
.152	Open hearth processes
.1	Acid
.2	Basic
.153	Bessemer processes
.1	Acid
.2	Basic
.154	Electric furnace processes
.16	**Carburization**
.161	Cementation process
.162	Crucible process
.17	**Founding**
.171	Melting
.172	Molding
.18	**Treatment**
.181	Heat treatment
.1	Hardening
.2	Tempering
.3	Annealing
.182	Case hardening
.183	Malleable cast iron process
.184	Mechanical treatment
.1	Forging
.2	Rolling
.3	Wire drawing
.4	Pressing
.5	Machining
.185	Finishing
.1	Sand blasting
.2	Pickling
.3	Painting
.4	Galvanizing
.5	Plating
.6	Oxidized coating
.7	Enameling

669.19 Plants

669.2 Gold and silver

.21 Gold alone
.211 Economic factors
.1 Sources
.2 Production
.3 Costs
.4 Purchasing power
.5 Uses
.212 Properties
.213 Alloys
.218 Chlorination
.1 Theory
.2 Vat chlorination process
.3 Barrel chlorination process
.219 Plants

.22 Silver alone
.221 Economic factors
.1 Sources
.2 Production
.3 Costs
.4 Prices
.5 Uses
.222 Properties
.223 Alloys
.228 Leaching
.1 Hot water leaching Ziervogel process
.2 Brine leaching Augustin process
.3 Hyposerlphite leaching
.31 Theory
.32 Patera process
.33 Russell process
.229 Plants

.23 Gold and silver
.231 Amalgamation
.1 Theory
.2 Plate amalgamation process
.3 Pan amalgamation process
.235 Smelting
.237 Refining and parting See 669.373, 669.473 and 669.573
.238 Cyanidation
.239 Plants

669.3 Copper

.31 Economic factors

669.311 Sources
.312 Production
.313 Costs
.314 Prices
.315 Uses
.32 Properties
.33 Alloys
.34 Roasting
.35 Matte smelting
.351 Reverberatory furnace process
.352 Blast furnace processes
.1 Smelting roasted ore
.2 Pyritic smelting
.36 Copper smelting
.361 Reverberatory furnace process for blister copper
.362 Blast furnace process for black copper
.363 Converting
.37 Refining
.371 Reverberatory furnace process
.372
.373 Electrolytic process
.38 Leaching
.381 Rio Jinto process
.382 Hunt and Douglas processes
.383 Neill process
.384 Henderson process
.39 Plants

669.4 Lead

.41 Economic factors
.411 Sources
.412 Production
.413 Costs
.414 Prices
.415 Uses
.42 Properties
.43 Alloys
.44 Roasting
.45 Smelting
.451 Ore hearth process
.452 Reverberatory furnace process
.453 Blast furnace process

669.46
.47 Refining
.471 Pattinson process
.472 Parkes process
.473 Electrolytic process
.48 Leaching
.49 Plants

669.5 Zinc
.51 Economic factors
.511 Sources
.512 Production
.513 Costs
.514 Prices
.515 Uses
.52 Properties
.53 Alloys
.54 Roasting
.55 Smelting
.56
.57 Refining
.571 Reverberating furnaces process
.572
.573 Electrolytic process
.58 Leaching
.59 Plants

.6 Tin

.7 Mercury and other metals

.8 General factors of roasting, smelting, refining
.81 Fuels
.811 Theory of combustion
.812 Solid fuels
.1 Wood
.2 Charcoal
.3 Peat
.4 Lignite
.5 Bituminous coal
.6 Coke
.7 Anthracite
.813 Liquid fuels
.814 Gaseous fuels

669.814.1	Natural gas
.2	Producer gas
.3	Water gas
.4	Coal gas
.5	Blast furnace gas
.82	**Refractories**
.821	Theory
.822	Siliceous refractories
.1	Sand
.2	Gannister
.3	Silica brick
.4	Carborundum and siloxicon
.823	Argillaceous refractories
.1	Fire clay
.2	Common clay
.824	Aluminaceous refractories
.1	Bauxite
.2	Fused alumina
.825	Carbonaceous refractories
.1	Graphite
.2	Carbon brick
.826	Chromitic refractories
.827	Alkaline earth refractories
.1	Magnesia
.2	Dolomite
.3	Lime
.828	Rare earth refractories
.7	Zirconia
.2	Tungsten
.829	Application and maintenance
.1	Cements
.2	Tamping implements
.9	Repair materials and methods
.83	**Furnaces**
.831	Roasting and calcining furnaces
.1	Theory of roasting and calcining
.2	Heaps
.3	Stalls
.4	Kilns
.5	Reverberatory furnaces
.51	Hand
.52	Mechanical
.521	With plane hearths
.522	With conical hearths
.523	With cylindrical hearths
.6	Muffles

669.831.7	Blast roasting furnaces	
.71	With intermittent discharge	Pots
.72	With continuous discharge	
.832	Smelting furnaces	
.1	Theory of smelting	
.2	Hearths	
.3	Reverberatory furnaces	
.31	Direct fired	
.32	Regenerative	
.4	Blast furnaces	
.5	Converters	
.6	Electric furnaces	
.833	Liquation furnaces	
.834	Distillation furnaces	Retorts
.835	Sublimation furnaces	
.836	Refining furnaces	
.837	Melting furnaces	
.84	Pyrometry	
.85	Flue gases and dusts	
.86	Slags	
.87	Mattes and speisses	
.88	Metals and alloys	
.89	Metallography	
669.9	**Sampling, assaying, preliminary operations**	
.91	Sampling	
.911	Sampling ores and fluxes	
.1	Theory	
.2	Taking samples	
.3	Preparing samples	
.9	Sampling works	
.912	Sampling metals	
.1	Theory	
.2	Methods	
.913	Sampling gases	
.1	Theory	
.2	Methods	
.92	Assaying	
.921	Fire assaying	
.922	Wet assaying	
.923	Electrolytic assaying	
.924	Coal analysis	
.925	Oil analysis	
.926	Gas analysis	

669.93 Drying
.94 Crushing
.95 Briquetting See 622.783 and 622.789.5

670 Manufactures

(In this division may be placed items that do not properly belong under 621; such as items relating to textile mills or machinery, the manufacture of shoes, etc.)

680 Mechanic Trades

690 Building

69 (001) Statistics
(002) Quantities and costs Prices, etc.
(003) Contracts and specifications
(01) Theories of construction
(02) Compends, treatises, text books, etc.
(07) Education, teaching, etc.

(See form divisions pp. 7 and 8)

691 Materials Processes Preservatives

For Strength of materials, see 620.1
For Uses of prepared materials, see 693 to 699

.1 Woods

.18 Preservation of woods

691.2 Natural stone Protection

.211 Limestone
.221 Granite
.231 Sandstone, ordinary
.24 Slate
.29 Preservation

.3 Artificial stone Concrete

.31 Beton coigniet
.32 Ransome
.33 Hollow block
.34 Selenitic
.35 Lime concrete
.36 Cement concrete
.37
.39 Aggregate

.4 Bricks Tiles Ceramic products

.46 Tiles
.47 Tiles, hollow structural

691.471 Floor
.472 Roof and ceiling
.48 Terra cotta
.49 Sewer tiles

.5 Lime Cement Plaster

.51 Lime, ordinary
.52 Lime, hydraulic
.53 Lime, selenitic
.54 Cement, natural
.55 Cement, portland or artificial
.56 Plaster of paris
.57 Keene's cement

.6 Glass

.7 Iron Steel Anti-rust processes

.71 Cast iron
.72 Malleable cast iron
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.74 Steel, blister or tool
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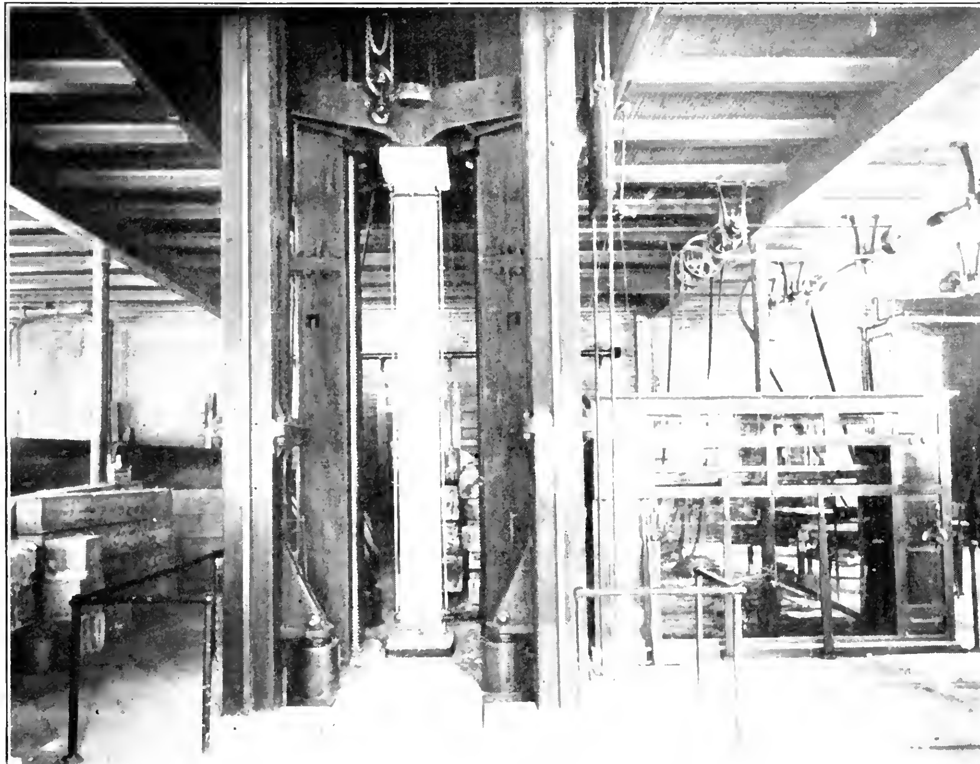

600,000 lb. Testing Machine with Column in Place.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 10 FEBRUARY 1907

TESTS OF CONCRETE AND REINFORCED CONCRETE COLUMNS; SERIES OF 1906

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS

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III. EXPERIMENTAL DATA AND DISCUSSION

I. Introduction

1. *Preliminary.*—Columns form an important element in reinforced concrete building construction. Many tests have been made on cubes and short prisms to determine the compressive strength of concrete. The method of making the test pieces and the conditions entering into the tests, as compared with the fabrication and testing of columns, do not permit the results of such tests to be taken as representative of the strength of concrete columns, the cubes generally having a stronger and more uniform concrete and the restraint of the bearing plates giving a higher relative load. Comparatively few tests have been made on columns, either plain or reinforced, and many of these, because of variation in material or age at test or other elements of strength, do not furnish data for comparison or conclusion. The tests herein recorded were made as a preliminary series, to open up the field for further experimentation here, and hence were not considered to be complete or to give full data or to follow in all respects the most approved methods of design, construction and testing. It is hoped, however, that the data and discussion will contribute somewhat to the knowledge of the strength and behavior of plain and reinforced concrete columns and perhaps serve to warn constructors against the use of high working stresses for columns constructed under ordinary working conditions and with concrete of moderate quality.

2. *Scope of Bulletin.*—Both plain and reinforced columns were tested. The reinforcement consisted of longitudinal rods. For part of the columns ties were carried around the reinforcing rods to hold them in place. Not only was the strength of the columns obtained, but the proportion taken by the concrete and by the steel has been estimated by means of the observed relation between the applied load and the resulting shortening of the column and through the use of the analysis herein given. This stress-deformation relation has also been utilized to determine other properties of the columns. Formulas for reinforced columns are given, and the constants to be used are discussed. As bearing on this, a discussion is made of the basis for factor of safety and working stress for plastic materials such as concrete under the conditions of the distribution and application of load to be found in columns. To permit a comparison to be made with the results

of other tests, a summary of the results of a series of column tests at Watertown Arsenal is included. It is felt that this comparison is a valuable addition.

3. *Acknowledgment.*—The investigation was made in the Laboratory of Applied Mechanics of the University of Illinois as a part of the work of the University of Illinois Engineering Experiment Station. The work of making the tests on the columns, cubes, and cylinders was done principally as thesis work by Ralph Corson Llewellyn, a senior student in architectural engineering, class of '06. Mr. Llewellyn is entitled to much credit for the intelligent thought and diligent care which he gave to the work, and much of the trustworthiness of the results is due to him. The review of the tests which he gave in the thesis was also quite creditable. Immediate supervision of the work of making the columns and of conducting the tests was given by D. A. Abrams, Assistant in the Engineering Experiment Station, whose aid in this and in interpreting the results has added much to the value of the work. Acknowledgment is also made to W. R. Robinson, Assistant in the Engineering Experiment Station, for valuable aid in the preparation of this bulletin.

The following division of the subject matter of the bulletin has been made: I. Introduction; II. Materials, Test Pieces and Method of Testing; III. Experimental Data and Discussion.

II. Materials, Test Pieces and Method of Testing

4. *Materials.*—The materials used in making the columns were similar to the building materials ordinarily used in concrete construction in the middle west. The sand, stone and cement were obtained in the open market.

Stone.—The stone was crushed limestone from Kankakee, Illinois. It was ordered to pass over a ¼-in. screen and through a 1-in. screen. Tests showed 54% voids, as found by pouring the stone slowly into water. The stone was nearly pure limestone, somewhat soft in quality.

Sand.—The sand was of good quality, well graded, sharp and fairly clean. It came from deposits near the Wabash river at Attica, Indiana. An average of five determinations showed it to contain 28% voids. The result of the mechanical analysis is given in Table 1.

TABLE 1.

MECHANICAL ANALYSIS OF SAND.

Sieve No.	Diameter of Mesh inches	Per cent Passing
4		100.0
10	.096	73.0
20	.040	36.0
50	.019	16.0
74	.011	5.0
100		2.0

Cement.—Chicago AA portland cement was used for all the tests. It was bought from a local dealer. Table 2 gives the

TABLE 2.

TENSILE STRENGTH OF CEMENT.

Ref. No.	Ultimate Strength, lb. per. sq. in.			
	Age 7 Days		Age 60 Days	
	Neat	1-3 Mortar	Neat	1-3 Mortar
1	634	283	890	443
2	717	281	916	440
3	732	275	840	442
4	687	217	942	365
5	580	206	872	352
6	731	189	885	
Av.	680	242	892	404

strength of standard briquettes of neat cement and of 1–3 mortar for age of 7 and 60 days.

Concrete.—Men skilled in mixing concrete were employed, and an effort was made to have the different batches of a uniform quality. All of the concrete was made of the proportions 1 of cement, 2 of sand, $3\frac{3}{4}$ of stone, measured by loose volume. It was intended to use a 1–2–4 mixture, but the large percentage of voids made it seem desirable to increase the amount of mortar. The concrete will, however, generally be referred to as a 1–2–4 mixture.

The mixing was done with shovels by hand. The sand and cement were first mixed together dry. The stone was then added and the mass turned several times with the shovels. When thoroughly mixed, water was added and the whole mass turned until uniform in appearance. A fairly wet mixture, as indicated further in the description of the making of the columns, was used, as this could be tamped into the forms to better advantage. The average weight of the concrete at the time of testing, figured from the weight of the cubes, was about 147 lb. per cu. ft.

Steel.—The reinforcement used in the columns consisted of plain round mild steel bars. It was furnished by the Illinois Steel Company and was an even grade of open hearth steel. Vertical rods, ¾-in. in diameter were used in the 12-in. columns and rods ⅝-in. in diameter in the 9-in. columns. All ties were made of ¼-in. round rods. The yield point of the steel averaged 39,800 lb. per sq. in., the ultimate strength averaged 59,200 lb. per sq. in., and the elongation in eight inches averaged 30.9 %. Table 3 shows the results of the tests of steel used in the columns.

TABLE 3.

TENSION TESTS OF STEEL USED IN COLUMNS.

Average Values.

Col. No.	Diam. inches	Per cent Elongation in 8 in.	Yield Point pounds	Maximum Load pounds	Yield Point lb. per sq. in.	Ultimate Strength lb. per sq. in.
1	.752	31.2	17600	26230	39750	59200
2	.618	32.4	11850	17850	39500	59500
3	.751	30.9	18100	27280	40870	62000
6	.622	30.1	11770	17710	38650	58300
7	.749	32.2	17640	25530	40030	58000
10	.623	31.8	12070	17920	39280	58820
11	.751	30.6	18480	26780	41820	60520
12	.623	31.8	12050	17800	37070	58470
14	.619	29.1	11900	18350	39450	60820
16	.623	30.6	11030	17460	39470	58100
17	.625	31.5	12130	17900	39500	58350
Av.	......	30.9	....	....	39800	59200

5. *Test Specimens.*—In making the test specimens, the effort was made to have the conditions of fabrication as nearly as possible the same in every case. In general two specimens of each kind were made, so that one would act as a check upon the other. Three types of specimens were made,—(a) cubes, (b) cylinders and (c) columns, the concrete for all being of the 1–2–3¾ mixture described above. Data for the test specimens are given in Table 4.

(a) Cubes.—17 cubes were tested, all of 12-in. edge. They were generally made in pairs, the concrete being taken from the mix used in the columns of corresponding number. The concrete for the cubes was taken from the middle of the batch, and is thought to be representative. In the case of columns mixed in two batches one cube was made from each batch. The concrete

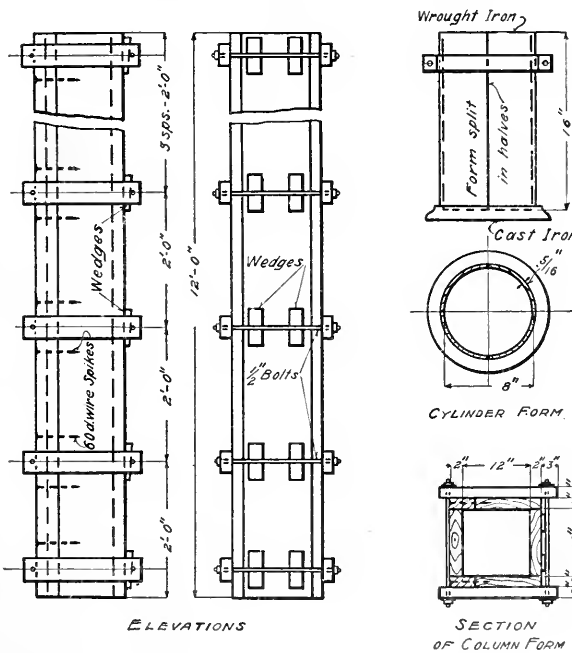


FIG. 1. FORMS FOR COLUMNS AND CYLINDERS.

was well tamped into the forms, and was troweled around the sides with a bricklayer's trowel to insure a good surface on the cubes. The conditions of storage were the same for the cubes as for the columns, the forms being taken off of correspondingly numbered specimens at the same time.

TABLE 4.

LIST OF TEST SPECIMENS.

Columns						Minor Specimens	
			Reinforcement				
Col. No.	Nominal Size in.x in.x ft.	Area of Cross-section sq. in.	Kind	Area sq. in.	Area per cent	Cubes	Cylinders
1	12x12x12	147.4	4—¾-in. rods	1.77	1.20		
2	9x 9x12	80.6	4—⅝-in. rods	1.23	1.52	Cube 2_1 Cube 2_2	
3	12x12x12	146.2	4—¾-in. rods 12—¼-in. ties	1.77	1.21		
4*	9x 9x12	182.0	Plain	0.	0.	Cube 4	
5	12x12x12	146.4	Plain	0.	0.	Cube 5_1 Cube 5_2	Cylinder 5
6	9x 9x12	80.9	4—⅝-in. rods	1.23	1.52		
7	12x12x12	145.5	4—¾-in. rods	1.77	1.21	Cube 7_1 Cube 7_2	
8	9x 9x12	80.8	Plain	0.	0.		
9	12x12x12	146.6	Plain	0.	0.		Cylinder 9
10	9x 9x12	82.0	4—⅝-in. rods 12—¼-in. ties	1.23	1.50	Cube 10_1 Cube 10_2	Cylinder 10_1 Cylinder 10_2
11	12x12x12	145.2	4—¾-in. rods 12—¼-in. ties	1.77	1.21	Cube 11_1 Cube 11_2	
12	9x 9x 9	82.7	4—⅝-in. rods 9—¼-in. ties	1.23	1.48		Cylinder 12_1 Cylinder 12_2
13	12x12x12	148.8	Plain	0.	0.		Cylinder 13
14	9x 9x12	82.0	4—⅝-in. rods 12—¼-in. ties	1.23	1.50		
15	12x12x 6	148.0	Plain	0.	0.	Cube 15_1 Cube 15_2	
16	9x 9x 9	82.5	4—⅝-in. rods 9—¼-in. ties	1.23	1.49	Cube 16_1 Cube 16_2	Cylinder 16_1 Cylinder 16_2
17	9x 9x 6	83.6	4—⅝-in. rods	1.23	1.47		
18	9x 9x 6	83.6	Plain	0.	0.		

*No. 4 was accidentally shattered in placing in machine and is not further considered.

(b) Cylinders.—Only 9 cylinders were tested. They were 8 in. in diameter and 16 in. long, and were made in the wrought iron forms shown in Fig. 1. They were made from the same concrete as the columns of corresponding numbers, and were treated in the same manner as the columns and cubes.

(c) Columns.—Three series of columns were made, one of plain concrete with no reinforcement, one reinforced with vertical rods in the corners only, and one reinforced with vertical rods in the corners tied together by ties of ¼-in. rods every 12 in. in height. All columns were made square in cross-section, two sizes being used, 9 in. and 12 in. Three lengths of columns were used,—6, 9 and 12 ft. The sizes and arrangement of the steel are shown in Fig. 2.

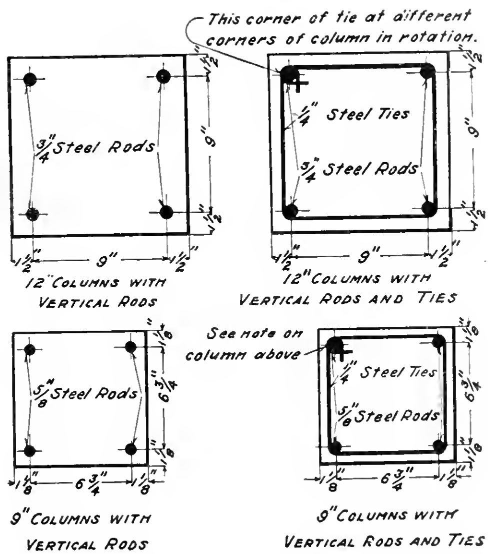


Fig. 2. Arrangement of Reinforcement.

The ties were made by bending ¼-in. steel rods while cold about a suitable form. The vertical rods were in all cases cut 1 in. shorter than the finished length of the column, it being intended to have ½ in. of concrete over the rods at each end. In some cases, however, the rods settled before the concrete set until the end was found flush with the bottom of the column.

6. *Forms for Columns.*—The forms for the columns were made of 2-in. pine plank, planed on both sides. Drawings of the forms

for the 12-in. columns are shown in Fig. 1, which are also typical of the forms for the 9-in. columns. Three sides of the forms were made of continuous pieces for the full height of the column, while the fourth side was made up of 2-ft. lengths. The forms were held together with braces of 2-in. x 4-in. pieces and ½-in. bolts. Wedges were used to adjust the form to the correct width and to hold it while the concrete was put in. It will be noticed that all parts of the forms are reversible, so that the sides can be turned over if they become warped through use. Three forms each were made for the 9-in. and the 12-in. columns, this number being sufficient to allow the forms to remain on the columns about two weeks before being needed for other specimens.

7. *Making of Columns.*—The forms were soaked in water for a few days before being set up. This kept the wood from drawing very much water out of the concrete and also decreased the tendency of the forms to warp. For the reinforced columns, the rods were put in place and fastened by temporary wooden blocks before any concrete was put in, the blocks being removed as the concrete was put into the forms. The concrete for the 12-in. x 12-in. x 12-ft. columns was mixed in two batches, care being taken to have both as nearly alike as possible. For all other columns, the concrete was mixed in one batch. The concrete was put in in 6-in. layers, each layer being thoroughly tamped or churned, troweled around the sides to improve the surface, and then tamped again. The consistency of the mixture was such that with a 4-in., 10-lb. tamper, efforts at tamping generally resulted in churning the mass, and water was constantly present on the top. When the column had been built up to the top of the first 2-ft. section of the open face of the form, another 2-ft. section was added, and the process carried on without intermission until the column was complete. In the columns with ties, the ties were placed 12-in. apart, as the concrete was filled in, the first tie being always 6-in. from the bottom of the column.

8. *Storage of Columns.*—The forms were allowed in most cases to remain on the columns for a period of 14 days after making. Nothing other than this was done to protect the surface of the columns from drying out too rapidly in the air. The temperature of the laboratory in which the columns were made ranged from 60° F. to 70° F. The forms protected the columns enough to prevent the warmer air at the top of the room from affecting the re-

sults of the tests to any great extent. The columns were not moved from the vertical position in which they were made until they were tested. It was intended to test each specimen at the age of 60 days but owing to a delay in receiving some of the instruments, the general age of the specimens was somewhat greater than this.

9. *Summary of Test Pieces.*—Table 4 gives a list of all the test specimens made, together with the size, and amount and kind of reinforcement. Specimens having corresponding numbers were made from the same batches of concrete. Columns 17 and 18 were not made with the same care as the other test specimens, being intended for 30-day preliminary tests, but finally were used at about the same age as the other columns.

10. *Testing Machines Used.*—The machine used in testing the columns and cubes was a Riehlé vertical screw machine with a capacity of 600,000 pounds. Because of its design, it was admirably adapted to carrying on the tests described here. The vertical screws are 36 inches apart, and a guide frame prevents any lateral movement of the head. The machine has six speeds, of which only the slowest, .05 inches per minute, was used in these tests. The frontispiece shows the machine, the scale case and controlling levers, and also a column in position for testing. The cylinders were tested on a 100,000-lb. Riehlé testing machine. The slowest speed of the machine, 0.1 inches per minute, was used for the tests.

11. *Method of Setting Specimens in Machine.*—Cubes.—The cubes were set in the machine in plaster of paris in a manner similar to that which will be described for the columns. Pieces of building paper were placed between the plaster and the bearing blocks of the machine to protect the latter.

Cylinders.—The cylinders were set in plaster and in addition a bearing block having two spherical surfaces of contact was placed above the specimen.

Columns.—The columns, when ready to be tested, were moved from the place where they were made to the machine by means of a four-legged crane, built especially for moving beams in the laboratory. This crane was high enough so that the columns could be raised vertically off of the floor by a block and tackle at one end of the crane. The tackle was fastened to a rope looped around the column slightly above its center of gravity, the top of the column being steadied by ropes tied to the top of the crane. After

being wheeled to the machine in this almost vertical position, two tackles on the machine were attached to opposite faces of the column near the top. The column could then be swung directly over the bearing block on the weighing table of the machine. A thin layer of rather slow-setting plaster of paris was then spread upon the bearing plate and the column lowered to a bearing in the plaster. Care was taken that the column was directly in the center of the machine and that it was plumb. The column was held in the proper position until the plaster bearing had set, after which the tackles were removed and a layer of plaster applied to the top of the column. The head of the machine was run down on this

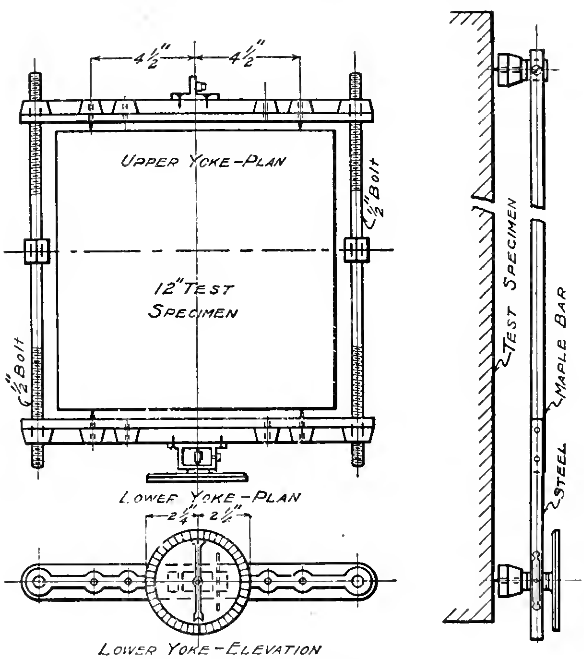


FIG. 3. EXTENSOMETER DEVICE.

plaster which was allowed to set under a load of several thousand pounds. A piece of galvanized sheet iron was used between the column and the pulling head of the machine to protect the latter from the plaster. This method of setting the columns in plaster assists in giving a uniform bearing over the entire area of the specimen.

12. *Measuring Devices.*—The shortenings or longitudinal deformations of the columns were read by means of an extensometer especially devised for these tests. (See Fig. 3). The extensometers were so arranged as to indicate the deformation in the center of each face of the column. The dials were arranged in pairs, those on opposite faces of the column being on the same yoke. The yokes were fastened to the column by means of four contact points, two on each opposite face. These contact points were 9 inches apart for the 12-in. and 6 inches apart for the 9-in. columns and were placed symmetrically with regard to the center line of the column. The two yokes carrying the dials were

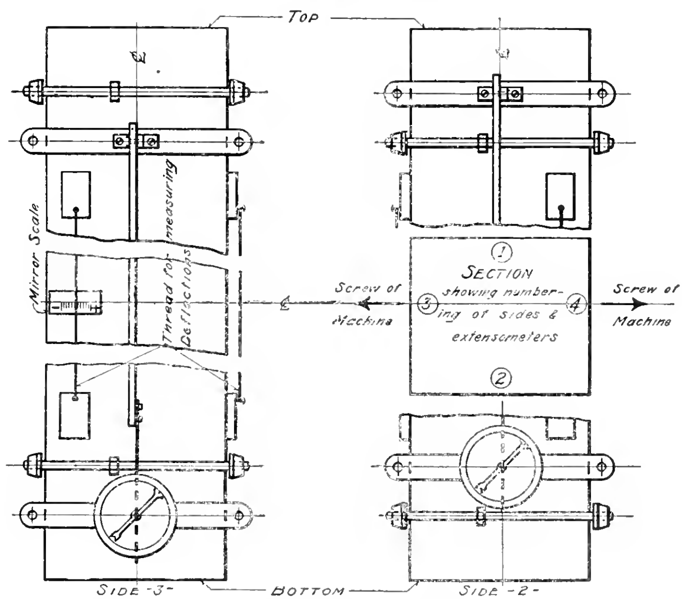


FIG. 4. ARRANGEMENT OF APPARATUS.

placed 3 inches apart at the bottom of the column, while the yokes carrying the corresponding extensometer bars were placed in a similar position at the top of the column. The gauged length was usually about 12 inches less than the length of the column. The extensometer bars were made of seasoned maple with steel blades at the ends to make contact with the rollers of the dials, which were so arranged that the blades of the extensometer bars could be held against the rollers by means of rubber bands. The dials, which were $4\frac{1}{2}$ inches in diameter, read to ten-thousandths

TABLE 5.

SUMMARY OF COLUMN TESTS.

Col. No.	Reinforcement		Maximum Load		Age days	Manner of Failure
	Kind	per cent	Total pounds	lb. per sq. in. of Gross Section		
1	4—$\frac{3}{4}$-in. rods	1.20	234000	1587	71	Crushed on one side, 4 ft. from bottom
2	4—$\frac{5}{8}$-in. rods	1.52	127000	1577	69	Crushed out near top
3	4—$\frac{3}{4}$-in. rods 12—$\frac{1}{4}$-in. ties	1.21	272000	1862	71	Crushed out 1 ft. from bottom. Rods finally buckled
5	Plain	0.	250200	1710	69	Crushed and sheared diagonally, 1$\frac{1}{2}$ ft. below top
6	4—$\frac{5}{8}$-in. rods	1.52	129400	1600	70	Crushed out 1 ft. from bottom. Rods finally buckled
7	4—$\frac{3}{4}$-in. rods	1.21	269000	1850	65	Crushed and sheared 5 ft. from bottom
8	Plain	0.	162000	2004	64	Top sheared off
9	Plain	0.	236000	1610	65	Crushed and sheared off at top
10	4—$\frac{5}{8}$-in. rods 12—$\frac{1}{4}$-in. ties	1.50	105000	1280	65	Crushed out 1 ft. from bottom. Rods finally buckled
11	4—$\frac{3}{4}$-in. rods 12—$\frac{1}{4}$-in. ties	1.21	281200	1936	65	Crushed 1$\frac{1}{2}$ ft. from top
12	4—$\frac{5}{8}$-in. rods 9—$\frac{1}{4}$-in. ties	1.48	193100	2335	66	Crushed 1 ft. below top
13	Plain	0.	254000	1709	61	Crushed in middle of length
14	4—$\frac{5}{8}$-in. rods 12—$\frac{1}{4}$-in. ties	1.50	112000	1367	63	Crushed 1$\frac{1}{2}$ ft. below top
15	Plain	0.	176000	1189	63	Crushed 1 ft. from top
16	4—$\frac{5}{8}$-in. rods 9—$\frac{1}{4}$-in. ties	1.49	132500	1607	59	Crushed at center Rods finally buckled
17	4—$\frac{5}{8}$-in. rods	1.47	184400	2206	67	Crushed 1 ft. from top. Rods finally buckled
18	Plain	0.	90300	1079	65	Crushed 1 ft. below top

of an inch. A clearer idea of the extensometers and method of using them may be obtained from Fig. 4 and also from the various photographs of the tests. Usually two men were engaged in taking the readings.

The lateral deflections of some of the columns were measured roughly by means of a thread and scale, fastened on the column as shown in Fig. 4. These readings were used only as a check on the way the column was deflecting.

13. *Application of the Load.*—In testing the columns, the load was applied in increments of about 10,000 pounds, the operator holding the load and the observers taking the readings about 30 seconds after the load was attained. The machine speed was .05 inches per minute. In six columns the load was increased progressively until failure occurred. In ten the load was released at one-third to two-thirds of the ultimate, and then reapplied. In one the load was released twice.

III. Experimental Data and Discussion

14. *Column Test Data.*—Table 5 gives data of the age of test, maximum load on column, and manner of failure. The proportion of the load taken by the concrete and by the steel is considered in a succeeding paragraph.

15. *Phenomena of the Column Tests.*—Most of the columns failed in either the top or bottom third of the length, only three failing at or near the center. Ten failed in the top third and four in the bottom third. The numerous failures near the top may possibly be due to drying out of the top of the columns, or more probably to the naturally greater porosity of the concrete there.

In most cases, little warning in the way of cracks or sounds was given before the maximum load was reached. Five of the columns, all reinforced ones, gave warning by noises or vertical cracks slightly before the concrete sustained the maximum stress. Eight columns, including all the plain ones, showed no sign of failure until the maximum load on the concrete was reached. The remaining four showed first sign of failure after reaching the maximum stress in the concrete but before the maximum load taken by the column as a whole was attained.

The plain columns failed suddenly, an explosive noise sometimes accompanying the crushing. The failure of the reinforced columns was usually first indicated by vertical hair cracks after

which the column commenced to bulge at the point of failure. Since in practically every failure the reinforcing rods buckled, it would seem at first thought that the failure was caused by a lateral deflection of the rods, resulting in splitting of the concrete outside the reinforcement, but in the discussion of the observations it will be shown that this buckling occurred after the failure of the concrete.

The following notes show the principal features of the tests of individual columns:

Column No. 1. At about the maximum load fine cracks appeared on one face 4 ft. above the bottom and soon spread to the adjoining face, but no crack appeared on the opposite face. Failure occurred at this point. Fig. 5 shows the appearance of the cracks on the face first showing sign of failure. At the maximum load the column deflected laterally at the middle of its length 0.22 in. in a direction away from the face on which failure first showed. This column gave the greatest lateral deflection measured, the next highest being only one-third as much. At a load of 167,000 lb. (1132 lb. per sq. in.) hair cracks appeared at the top of the column but these did not develop further. With the continued application of the load after the maximum had been reached, the concrete broke out, accompanied finally by buckling of the reinforcing rods.

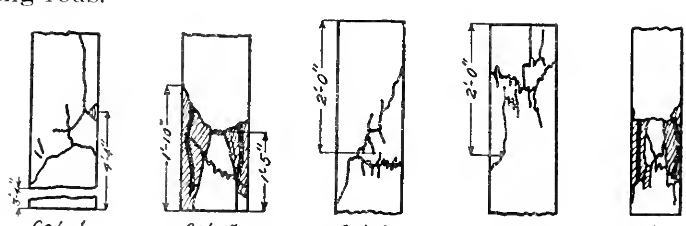


FIG. 5. TYPICAL FAILURES.

Column No. 2. Failed by crushing at top, the first crack appearing near one corner at the maximum load. Failure occurred immediately. A few cracks had appeared at the bottom of the column but these did not develop further. It would appear that the top end was weaker than the remainder of the column.

Column No. 3. Failed by crushing at a point 12 inches above the bottom at the maximum load. With continued application, all vertical rods buckled between the two ties. Fig. 5 shows the final condition at the point of failure.

Fig. 6. Views Showing Column No. 7 and 16 after Failure.

Column No. 4. This column was accidentally broken in setting it in the machine. It is not considered in this report.

Column No. 5. Failed at maximum load by crushing and shearing off completely on a diagonal line. No warning cracks appeared before maximum load was reached. The shearing plane extended from a point 9 in. below the top on one face to 2 ft. 5 in. on the opposite face.

Column No. 6. In this column the reinforcing rods extended through to the bottom of the concrete and thus had a direct bearing on the bed of the machine. The first crack appeared just before the maximum load taken by the concrete was reached. Failure occurred by compression of the concrete 12 in. above the base, and with continued application of the load the rods buckled at this point.

Column No. 7. Failed by compression of the concrete at a point about 5 ft. above the base, followed a little later by buckling of the rods. With continued application of a load nearly as great, the column finally sheared off diagonally with a loud explosive noise to a point 2 ft. 6 in. above the base. Fig. 6 shows the manner of failure. The greatest lateral deflection was 0.05 in.

Column No. 8. Failed without warning cracks by crushing at the top and shearing diagonally to a point 2 ft. 4 in. below.

Column No. 9. Failed without warning cracks and without noise by crushing diagonally about 18 inches below the top. Fig. 5 shows two faces.

Column No. 10. Failed by crushing out between the bottom two ties, 12 in. from the base. The concrete broke out near the vertical rod on one corner. This rod was found to rest directly upon the bed of the machine at the completion of the test. The lateral deflection was .02 in. Fig. 5 shows one face after failure.

Column No. 11. A corner was knocked off of the top of the column for a distance of $2\frac{1}{2}$ in. each way while setting it in the machine. Failure occurred by crushing between upper two ties 16 in. below the top after the maximum stress on the concrete had been passed. The lateral deflection was .07 in.

Column No. 12. Failed by crushing between upper two ties 13 in. below the top. First crack appeared at maximum load on the column, after the maximum stress on the concrete had been passed. Crackling sounds were heard at 2,275 lb. per sq. in.

Column No. 13. Failed by crushing nearly squarely across at the center of the height of the column. Vertical cracks extended half the length of the column. No cracks appeared before maximum load was reached.

Column No. 14. Failed by crushing at from 12 to 22 in. below the top. With continued application of the load the rods buckled between the top two ties. Maximum lateral deflection of column was .02 in.

TABLE 6.

TESTS OF CUBES AND CYLINDERS.

Cubes				Cylinders			
No.	Age at Test days	Maximum Load Total pounds	Maximum Load lb. per sq. in.	No.	Age at Test days	Maximum Load Total pounds	Maximum Load lb. per sq. in.
2_1	67	282400	1970	5	68	85600	1758
2_2	67	280000	1954	9	59	55000	1112
5_1	61	333100	2314	10_1	80	52000	1068
5_2	61	368700	2572	10_2	80	61000	1233
7_1	69	256500	1790	12_1	78	100320	2088
7_2	70	383000	2672	12_2	80	95000	1920
10_1	64	273100	1897	16_1	69	75500	1525
10_2	76	332500	2308	16_2	69	59100	1212
11_1	75	353500	2453				
11_2	75	337000	2340				
15_1	67	282400	1970				
15_2	67	280000	1954				
16_1	66	305100	2090				
16_2	66	348000	2417				
18_1	39	213000	1472				
18_2	39	223400	1550				
Av.	....	....	2100	......	....	....	1490

Column No. 15. Failed by crushing at about 12 in. from the top, vertical cracks appearing on all sides when maximum load was reached. No cracks appeared previously.

Column No. 16. Failed by crushing near the center of the length of the column, the first crack appearing just before the maximum load on the column, and some time after the max-

imum stress in the concrete had been reached. With further application of the load vertical rods buckled between three successive ties.

Column No. 17. Failed by crushing at maximum load 12 in. below the top. Rods finally buckled between top two ties.

Column No. 18. Failed by crushing at maximum load 12 in. below top. This column showed poor concrete.

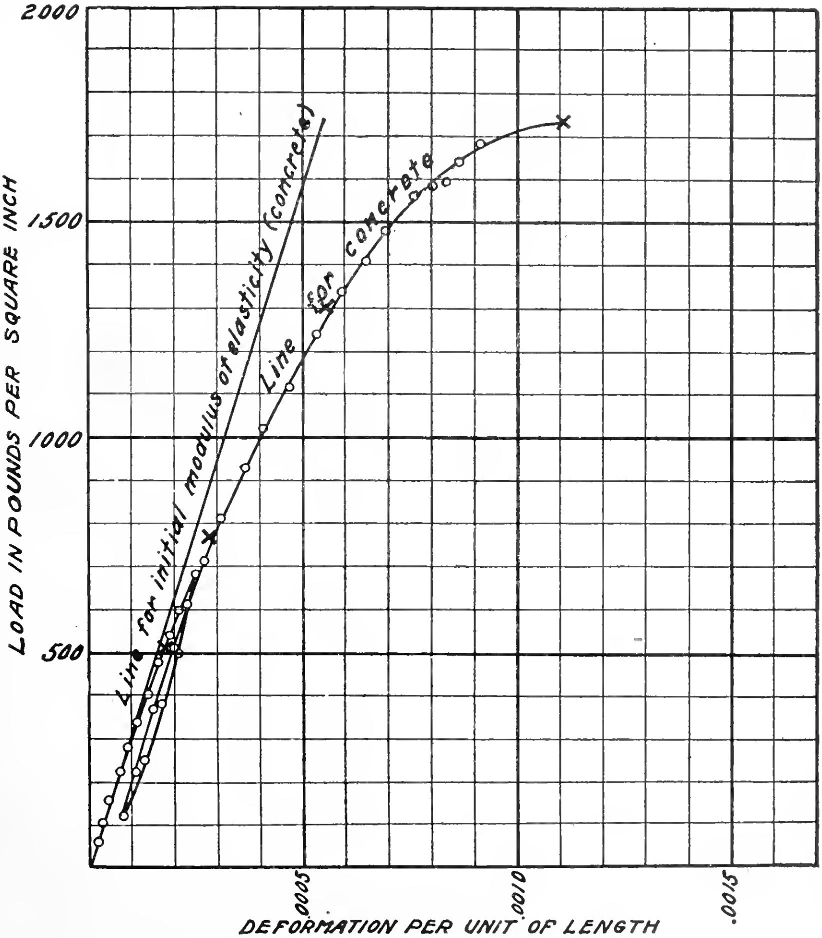


FIG. 7. STRESS-DEFORMATION DIAGRAM FOR COLUMN NO. 5.

16. *Cube and Cylinder Test Data.*—Table 6 gives data of the age at test and of the compressive strength of the cubes and cyl-

inders which were made from the same batches of concrete as the corresponding columns. Reference to the strength of the con-

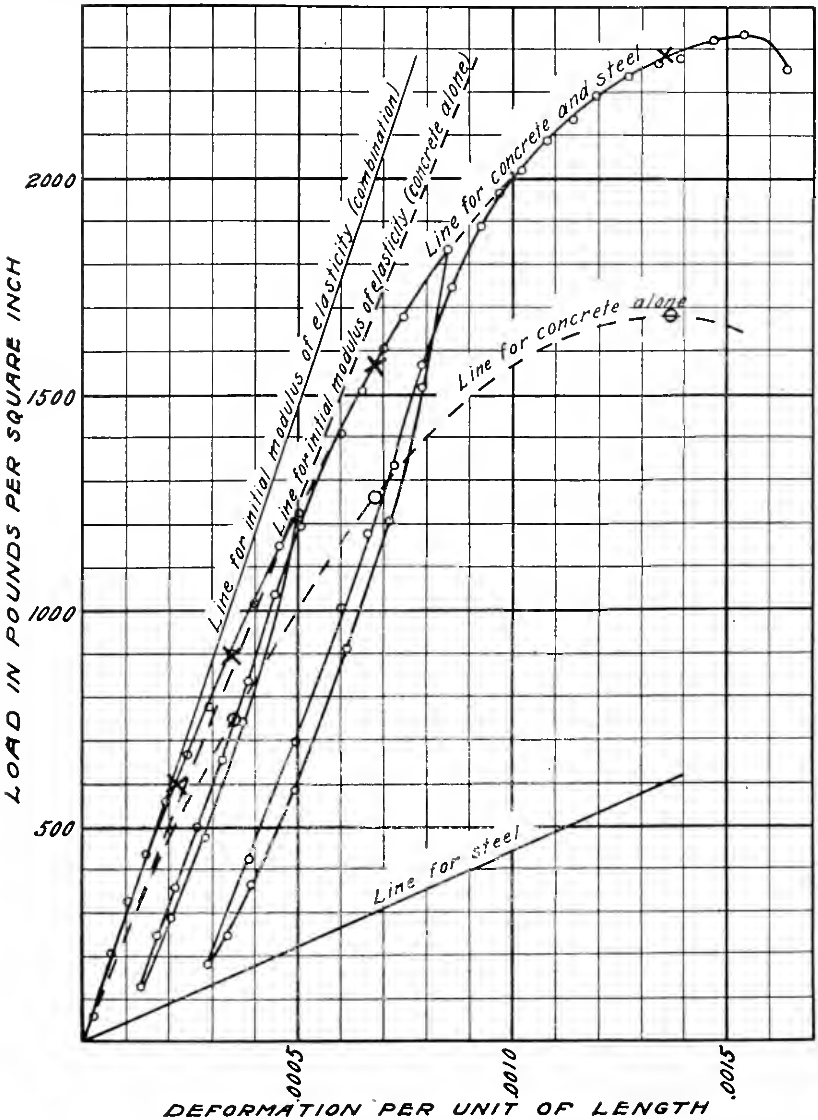


FIG. 8. STRESS-DEFORMATION DIAGRAM FOR COLUMN NO. 12.

crete in the columns given in Tables 7 and 8 shows that the cubes

and cylinders correspond to the weaker rather than to the stronger columns.

17. *Stress-deformation Diagrams.*—In Fig. 13 to 29, following the text, and in the sample figures (Fig. 7 and Fig. 8) given in the text, the stress-deformation diagrams represent the observed loads and the corresponding deformations or shortenings for the columns tested. The ordinates (vertical distances on the diagram) represent the loads or pressure per square inch on the columns. For the reinforced concrete columns, for convenience of calculation, the unit-loads given on the diagram are based upon the gross area of the column. The bearing of this assumption upon the stresses in the concrete is discussed elsewhere. The abscissas (horizontal distances on the diagram) represent the unit-deformations, or shortenings per unit of length, determined from the observed extensometer readings for the gauged length used. These values are the averages for the readings on the four faces of the column. In general, the readings on the four faces varied but little from each other, as would be the case if the head of the machine moved parallel with itself and the column deflected laterally but slightly.

In these diagrams the amount of deformation is calculated by using as the zero reading the extensometer reading at the original zero of load or load at which the first reading was taken. In other words, the deformation shown is independent of any set which the load may have produced in the concrete. Whether gross or net (elastic) deformations are to be considered in discussing the results of tests depends, of course, on the use which is to be made of the results. In a discussion of the action and effect of longitudinal reinforcing bars, it would seem that gross or total deformations should be used rather than net or elastic deformations, and this is one reason for choosing to use gross deformations here. Since nothing is known of the shrinkage stresses in the concrete and steel, no consideration of their effect will be made.

The "Line for initial modulus of elasticity" given on the diagrams is the tangent at zero load for a parabola which has been found to fit the stress-deformation curve closely. The analysis and formula for the parabola and the initial tangent are given in a succeeding paragraph. In the choice of parabola for a given stress-deformation curve, the effort has been made to fit the curve fairly closely, but a fair correspondence between the ordinate for

the vertex of the parabola and the ultimate strength of the concrete has been looked for and also an agreement of the vertex with the deformation of the concrete at the maximum load. While some variation may be found in the exercise of the judgment in determining this parabola, yet the range of choice is less than is found when attempting to select a straight-line modulus through the early part of the curve.

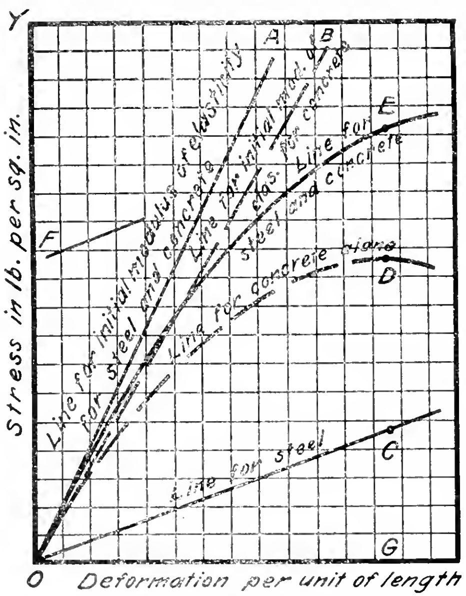


FIG. 9. STRESS-DEFORMATION DIAGRAM FOR A REINFORCED CONCRETE COLUMN.

The line marked "Line for steel" represents for any given deformation the load per square inch considered distributed over the area of the column which is equivalent to that taken by the steel alone, considering the modulus of elasticity of the steel to be 30,000,000 lb. per sq. in. Thus, for a deformation in the column of .001, the corresponding stress in the steel is 30,000 lb. per sq. in. For a column having steel reinforcement equal to $1\frac{1}{2}\%$ of its cross section, the load thus taken by the steel is equivalent to 450 lb. per sq. in. distributed over the whole cross section, and the "Line for steel" is drawn through 450 lb. per sq. in. and a unit deformation of .001. For any given deformation, then, the amount of load below this line represents, on this basis, the part taken by

the steel reinforcement, and the amount above this line represents the part taken by the concrete. To illustrate, in Column No. 12 (Fig. 8) for a deformation of .0005 the steel will, by this analysis, be taking the equivalent of 220 lb. per sq. in. distributed over the cross section of the column (15,000 lb. per sq. in. on the steel alone), and the concrete will be taking 1,020 lb. per sq. in.; for a deformation of .001, the steel will be taking the equivalent of 440 lb. per sq. in. (30,000 lb. per sq. in. on the steel alone), and the concrete 1,560 lb. per sq. in. Strictly speaking, the amount so found should be increased by a percentage equal to that occupied by the steel area, since the former calculation assumes that this area is occupied by concrete, but as the effect of this correction is small it has been neglected.

In the case of the plain concrete columns, the maximum load may be expected to occur at or before the vertex of the parabola. Evidently, even if such a curve as the parabola fits the stress-deformation curve fairly well for low and medium loads, it may not be expected to agree so closely near the maximum, and beyond the maximum load such a law of course is not applicable. Fig. 7 shows the stress-deformation curve and points on its parabola for Column No. 5. In this and in Fig. 13 to 18 at the end of the text, several points of the parabola which is taken to express the stress-deformation relation have been calculated for the columns and are shown on the diagrams by points marked by crosses. These are given at deformations equal, respectively, to one-sixth, one-quarter, one-half, and full abscissa of the vertex of the parabola. The last one given is for the vertex of the parabola.

In the case of the columns reinforced with longitudinal rods, (1) a new diagram may be made to express the load taken by the concrete alone, or (2) the stress-deformation line may be considered to be drawn according to a modified system of oblique co-ordinates. In Fig. 9 the line OE represents the stress-deformation relation for the combination of steel and concrete and OC that for the steel. For (1), if the point E be set down to D a distance ED equal to CG, the ordinate GD will represent the stress taken by the concrete alone at this point. If, now, the amounts taken by the concrete alone, found on the above basis, be replatted, using the line OX as an axis, the new line OD marked "Line for concrete alone" will be the stress-deformation diagram for the concrete itself, and will be found to approximate to a parabola as in the

plain concrete columns. The resemblance of this curve and tangent to those for the plain concrete columns is at once apparent. (In Fig. 8, a diagram for the concrete alone is shown for Column No. 12.) The line OB is the tangent for this curve, or line for initial modulus of elasticity. By (2), the representation by a modified system of oblique co-ordinates, the ordinates or loads taken by the concrete are measured from the oblique line marked "Line for steel", and the shortenings of the column are measured horizontally as before. In Fig. 9, CE will represent the stress in the concrete at its maximum load, and the stresses in the concrete for other deformations will be found by measuring upward from the line OC. The separate diagram gives a good expression of the stress in the concrete itself. However, the line OE (Fig. 9) represents this stress-deformation relation as well, if we keep in mind that ordinates are to be measured from OC, and that diagonal distance or spaces are misleading. OA, which will represent the line for the initial modulus of elasticity in this combination or oblique diagram, will be above OB, and any point of it will be as much higher as the vertical distance of the corresponding point on OC is above OX. This line OA, from its distorted position, may not seem to be tangent to the curve OE. The point E on the oblique or combination parabola, directly above the vertex D of the ordinary parabola, must be considered to be the vertex of the oblique parabola, and is the point where the maximum load is taken by the concrete according to this stress-deformation relation, as is shown by the tangent line EF being parallel to OC. Beyond this point, while the column as a whole may sustain a larger load, a greater proportion of the load is taken by the steel, and the concrete has passed its maximum carrying capacity. In general, then, the point at which the concrete carries a maximum amount may be obtained by finding the point (as E) where a line parallel to the line for steel (OC) is tangent to the stress-deformation curve and then determining the load above the line for steel. This value, represented by CE, may then be considered the maximum load taken by the concrete. The values given in the discussion which follows were calculated on this basis. This analysis, as is shown later, is borne out by the results of the columns tested. Although the oblique or combination diagram may strike the reader strangely, it was not thought necessary to reduce the readings to ordinary rectangular co-ordinates and make a second set of diagrams.

The diagrams given in Fig. 19 to 29, while at first perhaps appearing distorted, will, it is believed, give a comprehensive view of the relation between the loads taken by the concrete and steel for any given deformation or shortening of the column.

18. *The Parabolic Stress-deformation Relation.*—To begin with, it may be premised that a study and analysis of the relation between the stress or load in pounds per square inch and the unit deformation or shortening of the concrete will be of considerable value in the discussion and interpretation of the phenomena of compression of concrete in plain and reinforced columns. This stress-deformation relation has an important bearing upon the strength of columns and on the proportion of load taken by the concrete and by the steel reinforcement in reinforced concrete columns. An analysis based on a curved stress-deformation relation, although not difficult, requires some little explanation. It is hoped, therefore, that the reader will go over the discussion fully with the applicability of such an analysis in mind and not hastily conclude that undue weight has been attached to the curved form of the stress-deformation relation. Nor should the reader consider that the use of the parabolic relation in this discussion commits the writer to the position of excluding the straight-line stress-deformation relation (constant modulus of elasticity) from use in any formulas or applications whatever.

In a general way it may be said that concrete does not possess the property of proportionality of stress and deformation for wide ranges of stress as does steel; in other words, the deformation or shortening produced by a load is not proportional to the compressive stress. The relation between stress and deformation is not entirely uniform; there are even considerable differences in deformations for the same mixture, but generally the variation from direct proportionality is less for the richer mixtures. Various curves have been proposed to represent the stress-deformation relation, but the parabola is the most satisfactory general representation Frequently the parabola expresses the relation almost exactly, especially for mixtures of medium richness, and in nearly every case the parabolic relation will fit the stress-deformation diagram very closely throughout the part which is ordinarily developed in columns, the lack of agreement near the crushing point not being so important. Fig. 7 and Fig. 8 show the close agreement of the observed stress-deformation curve and the parabolic relation for Columns No. 5 and 12.

Modulus of elasticity is a term which has been used very loosely in connection with reinforced concrete. As a general property of materials, it is defined to be the ratio of the unit stress to the unit deformation within the elastic limit of the material. As applied in this way to materials having the property of proportionality of stress and deformation, the modulus of elasticity is a constant. For materials with a variable stress-deformation relation like concrete it may not be considered proper to call the variable ratio the modulus of elasticity, and such a use may lead to misunderstanding. However, it is important that a definite expression for this ratio be found.

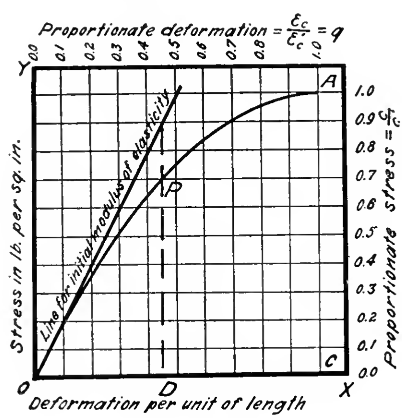


FIG. 10. STRESS-DEFORMATION DIAGRAM FOR A PLAIN CONCRETE COLUMN.

The writer obtains this relation from the initial modulus of elasticity and uses the term "Initial Modulus of Elasticity" to express the relation which would exist between stress and deformation if the concrete compressed uniformly at the rate it compresses when the load is first applied. For the parabolic stress-deformation relation, the line which represents this uniform or constant stress-deformation relation will be tangent to the parabola at the zero point. In Fig. 10 the ordinates represent unit stresses (pounds per square inch) and the abscissas unit deformations (shortenings in inches per inch). The relation between the stresses and the corresponding deformations may be represented by the part of a parabola, OA, which has its vertex at A, AC being its axis. The oblique line is tangent to the parabola at O, and

the tangent of the angle which it makes with the vertical is E_c, where E_c is the value of the initial modulus of elasticity. The equation of this line is $x = E_c y$, and this equation would give the relation between the compressive stress and the deformation if the stress-deformation relation were constant; or in other words if the modulus of elasticity were a constant.

The equation of the parabola may best be expressed by its relation to this line for initial modulus of elasticity. Let c represent compressive unit-stress for any point, (for the point P the ordinate DP represents c) and c' the maximum compressive stress (ordinate of vertex of parabola, CA). Let ϵ_c represent the unit-deformation for the point P (abscissa OD) and ϵ_c' the unit-deformation corresponding to the maximum compressive stress (abscissa of the vertex of the parabola, OC). It can be shown that $c = E_c\epsilon_c - \frac{1}{2}\frac{1}{\epsilon_c'}E_c\epsilon_c^2$ may be taken as the equation of the parabola. On this basis, this equation expresses the relation between the compressive stress and its corresponding deformation. It may be noted that the first term of the second member gives the stress corresponding to a given deformation by the straight-line relation, while the remaining term expresses a correction or reduction which changes the results materially for the higher deformations.

The value of the deformation at the maximum compressive strength of concrete, ϵ_c', (abscissa of the vertex of the parabola), enters into equation (1). For many applications, it is convenient to express the deformation as a part of or in terms of this vertex deformation. Call the ratio of the deformation developed at a given load to the deformation at the maximum load q (i. e., $q = \frac{\epsilon_c}{\epsilon_c'}$) and the foregoing equation becomes

$$c = E_c\epsilon_c - \frac{1}{2}\frac{1}{\epsilon_c'}E_c\epsilon_c^2 = (1 - \tfrac{1}{2}\, q)\; E_c\epsilon_c \quad \ldots\ldots\ldots\ldots (1)$$

The following relation may also be derived

$$\frac{c}{c'} = (1 - \tfrac{1}{2}\, q)\, 2\, q. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

When this parabolic relation is used the value c' will refer to the stress for the vertex of the parabola and ϵ_c' as its correspond-

ing deformation or abscissa. These may vary somewhat from the maximum compressive strength of the concrete and its corresponding deformation, but not greatly. The two sets of values should not be confused.

In Fig. 10 it may be seen that for the lower ranges of stress the parabola does not vary greatly from the straight line. At the

TABLE 7.

PLAIN CONCRETE COLUMNS.

Col. No.	Gauged Length inches	Initial Modulus of Elasticity lb. per sq. in.	Abscissa of Vertex of Parabola	Maximum Stress lb. per sq. in.	
				Parabola	Observed
5	114	3 150 000	.0011	1730	1722
8	114	2 530 000	.0016	2000	2004
9	114	2 500 000	.0013	1620	1615
13	60	2 370 000	.0014	1660	1709
15	60	2 000 000	.0012	1200	1189
18	60	1 490 000	.00145	1080	1079
Av.	....	2 340 000	.00134	1550	1553

vertex, however, the compressive stress (representing the maximum compressive strength) is one-half of that given by the straight-line relation. At one-half of ultimate deformation ($q = \frac{1}{2}$) it is three-quarters of that given by the straight-line relation.

The modification of the stress-deformation relation when longitudinal reinforcement is introduced has already been described.

19. *The Stress-deformation Relations Developed in the Columns.*— It will be well to discuss the stress-deformation relations found in the columns tested, not so much because of the importance of the relations themselves, but for the reason that the results throw light upon the strength, stiffness, uniformity, and reliability of the columns. The diagrams (Fig. 13 to 18, following the text) contain the stress-deformation curves for the plain concrete columns. As has already been stated, these diagrams are based upon gross or total shortenings and not on net or elastic defor-

mations, since one use of the data will be to permit comparison, in the case of columns having longitudinal reinforcement, of the amount of load taken by the concrete with that taken by the steel, and the use of elastic deformation would involve consideration of stresses left in the steel upon release of load.

An examination of these diagrams shows that the maximum loads on the columns are in agreement with the stress-deformation diagrams, no column failing at a lower load than would be expected from a study of its diagram. The porous nature of Column No. 18 (a column made with less care than was given to the others) is shown by its diagram, (Fig. 15), which early gives indication of the low ultimate strength. The points given on these figures (denoted by crosses) for the parabolic stress-deformation relation agree, in general, fairly closely with the diagrams.

Table 7 gives for the plain concrete columns values for the initial modulus of elasticity, the deformation at the point of maximum strength used (abscissa of vertex of parabola), the maximum stress shown by the parabolic relation and the observed maximum compressive strength of the parabolic relation and the observed maximum compressive strength of the column. Except for Columns No. 5 and 18, both the modulus of elasticity and the abscissas of the vertex of the parabolas have a small range, and even including these the results show as small variation as may be expected in concrete made in this way. The average value for the initial modulus of elasticity, 2,340,000 lb. per sq. in., not only is of interest in its application to columns but it may have a bearing upon the value to be used in beam formulas. It should be noted that these values are for the first application of a load. For a repetition of a load the modulus of elasticity would be somewhat lower than this, the amount of this decrease depending upon the concrete and the number of repetitions. The average value for the abscissa of the vertex of parabola is .00134.

Table 8 gives similar values for the reinforced concrete columns. The amount of load taken by the concrete was found by the method described under Stress-deformation Diagrams, and the initial modulus of elasticity was taken from the derived stress-deformation curve for concrete alone. The abscissa of the vertex was found in a similar way. The maximum stress taken by the concrete was determined from the point on the stress-deformation curve at which a tangent is parallel to the line for the steel.

It will be seen by inspection of the diagrams that the column as a whole takes a load somewhat greater than that which gives the maximum stress on the concrete, the increase coming from the increased stress in the steel, though the amount of this increase

TABLE 8.

REINFORCED CONCRETE COLUMNS.

Col. No.	Gauged Length inches	per cent Reinforcement	Initial Modulus of Elasticity lb. per sq. in.	Abscissa of Vertex of Parabola	Maximum Stress in Concrete lb. per sq. in.		Maximum Stress on Gross Area lb. per sq. in.
					Parabola	Observed	
1	132	1.20	2 570 000	.00095	1220	1220	1587
2	108	1.52	2 330 000	.0010	1165	1160	1577
3	132	1.21	2 340 000	.0012	1400	1380	1862
6	132	1.52	2 090 000	.00105	1095	1090	1600
7	132	1.21	2 570 000	.0011	1410	1400	1850
10	132	1.50	1 800 000	.0009	810	775	1280
11	132	1.21	2 430 000	.0012	1460	1460	1936
12	95	1.48	2 500 000	.00135	1687	1685	2335
14	132	1.50	2 000 000	.00095	950	955	1367
16	95	1.49	1 900 000	.00105	1000	990	1607
17	60	1.47	1 900 000	.0016	1520	1560	2206
Av.	.....	......	2 220 000	.00112	1247	1243	1746

averages only 2.2% and the largest increase is only 6.6%. The range of values for the initial modulus of elasticity is not greater than for the plain concrete columns, nor is that for deformation at vertex of parabola.

The last column of Table 8 gives the maximum load taken by the column in lb. per sq. in. of gross area, and hence includes the load taken by the steel.

The average value of the initial modulus of elasticity for the reinforced concrete columns is 2,220,000 lb. per sq. in. The average value of the final unit-deformation is .00112. The average variation from the average modulus of elasticity is 11%. The average variation from the average final deformation is 14%. The average value of the initial modulus of elasticity, 2,220,000 lb.

per sq. in., is very close to that for the plain concrete column, 2,340,000 lb. per sq. in. The final deformation is lower than that for the plain concrete columns. The range of results is smaller than that for the plain concrete columns.

The average modulus of elasticity for both plain and reinforced columns is 2,250,000 lb. per sq in. The average variation from this is 14%. The range covered is 40% above the average and 34% below, the extreme cases both being plain concrete columns.

Table 9 gives the observed and calculated loads for both plain and reinforced columns at four points of the tests. The loads include both the part taken by the concrete and that taken by the steel. The calculated loads are determined from the initial modulus of elasticity and parabola given in Tables 7 and 8. In the table, ϵ_c' represents the deformation at the point of maximum stress in the concrete, which agrees with the abscissa of the vertex of the parabola used. The values given in the last column therefore may not be expected to agree with the values given in Table 8 for maximum stress on gross area.

The three other points selected are at deformations of one-sixth ($q=\frac{1}{6}$), one-quarter ($q=\frac{1}{4}$) and one-half ($q=\frac{1}{2}$) of this deformation. It will be seen that the observed and calculated loads compare very favorably. The calculated loads are also shown in Fig. 13 to 29 (following the text) by points marked by crosses. Values for the Watertown Arsenal column tests, described elsewhere, are included in Table 9.

20. *Strength of the Plain Concrete Columns.*—Naturally, with the variation in materials and in the conditions attending fabrication and setting, concrete columns may not be expected to have uniform strength and stiffness. The conditions attending the fabrication of test specimens, however, are more nearly constant than those to be found in ordinary building operations and a greater allowance for variation should be made in building design than the variation found in these test columns. No. 18, which was made hastily and somewhat carelessly, with the expectation that it would be used at an early age merely for practice in the use of the instruments and machine, gives not only less stiffness but a very low compressive strength.

TABLE 9.

CALCULATED AND OBSERVED LOADS.

Loads are given in pounds per square inch of the gross section of the column and hence include the load taken by the steel.

Col. No.	At $\frac{1}{6}\epsilon'_c$		At $\frac{1}{4}\epsilon'_c$		At $\frac{1}{2}\epsilon'_c$		At ϵ'_c	
	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.
			University of Illinois Columns.					
1	440	435	610	600	1085	1055	1560	1560
2	430	430	625	620	1105	1080	1620	1570
3	505	545	725	745	1270	1265	1840	1815
6	400	415	600	600	1065	1045	1575	1570
7	500	515	720	705	1260	1300	1815	1810
10	315	315	440	435	805	785	1210	1205
11	520	540	750	750	1320	1310	1900	1895
12	605	630	895	910	1575	1575	2290	2290
14	365	385	525	535	915	910	1370	1375
16	380	415	550	555	980	960	1450	1450
17	595	540	845	820	1490	1535	2230	2200
5	520	520	770	745	1300	1275	1730	1720
8	610	630	875	880	1500	1435	2000	2005
9	495	490	710	690	1220	1150	1620	1620
13	505	505	725	710	1240	1170	1660	1710
15	370	385	525	525	900	860	1200	1190
18	330	345	475	475	805	765	1080	1080
Av.	463	473	662	664	1167	1146	1656	1651
			Watertown Arsenal Columns					
1579	805	830	1130	1130	1920	1920	2800	2800
1580	557	555	755	750	1260	1280	1820	1830
1581	640	610	885	880	1480	1475	2080	2060
1582	650	620	905	860	1500	1450	2110	2110
1584	820	820	1170	1110	1980	1930	2870	2870
1585	675	630	930	870	1600	1550	2460	2460
1583	645	650	890	890	1450	1420	1800	1800
Av.	685	673	952	927	1598	1575	2277	2275

The average maximum load for the plain concrete columns tested, as shown in Table 7, was 1553 lb. per sq. in. The lowest load, 1079 lb. per sq. in. for Column No. 18, is 30% less than this

average, and the highest load, 2004 lb. per sq. in., is 29% more than this average. The average variation from the average strength is 18%. This range is not large, considering the nature of the material. As has been stated, the stress-deformation diagrams indicate that the maximum loads found correspond with the general behavior of the columns and that the test loads were generally concentrically applied and uniformly distributed. They also show the variation in quality and action. The diagram of No. 18 shows its porous nature and foretells failure at a low load. No general difference in results between 9 x 9-in. and 12 x 12-in. columns is noticeable.

A comparison of the ultimate strength of the cubes tested with the loads carried by the columns made with the same mix shows that the strength of the columns is materially less than the strength of the cubes. As shown in Table 6 the average for the 12-in. cubes is 2205 lb. per sq. in. and that for the columns is 1553 lb. per sq. in., 30% less. It seems probable that the restraining influence of the friction against the bearing plates is a cause for the additional strength in the cubes, as has been shown by some experimenters to be the case, while in the columns this influence does not extend far from the ends. The results with the 8 x 16-in. cylinders given in the same table (average of 1490 lb. per sq. in.) agree very closely with the column tests and corroborate this view.

21. *Strength of the Reinforced Concrete Columns.*—Two things are noticeable in the results given in Table 8 for the loads taken by the concrete in the columns reinforced with longitudinal rods,—that the maximum stresses taken by the concrete are less than for the plain concrete columns, and that the range of results is greater. Before discussing these apparent characteristics of the tests, it will be well to consider some of the conditions attending the tests and the possible effect of such conditions upon the results.

No effort was made to bring the ends of the reinforcing rods to have a bearing upon the compression or bearing plates of the testing machine. Generally, the rods ended within ½ in. of the end of the column. In No. 6, the rods rested on the bearing plate; in No. 10, one rod rested on the plate; and in No. 14, the rods extended to the face of the plaster in which the ends of the columns were bedded. Evidently it would be difficult to get an exact and even bearing for all the rods directly against the plates. The

concrete or plaster under the ends of the rods would not be capable of transmitting as great a stress per square inch as is taken by the steel, and part of the load taken by the steel must be carried through the surrounding concrete and be transmitted to the steel by means of the bond between concrete and steel. Fortunately this extra stress on the concrete exists at the ends of the columns where the concrete has the aid of the lateral restraining influence of the bearing plates. The bond developed would cause the stress to be transmitted to the rods within a short distance of the end of the column. Whether this is done before the concrete is beyond the influence of the bearing plates and whether the bond developed is beyond the bond strength may, perhaps, be determined by a study of the stress-deformation diagrams and the method and point of failure of the individual columns. The yokes of the extensometers were in general within the portion of the length where the rods may be considered to be taking their full stress, and the deformations are the average deformations for the gauged length.

In all of the columns the point of maximum stress on the concrete is well within the point of ultimate failure, the deformation of the columns going on for some time beyond this maximum point. The form of the stress-deformation curve is similar for all the columns, and no difference can be detected for those with different positions of the ends of the reinforcing rods. The method of failure and the position of the failure are not noticeably connected with any end condition, and the distribution of the failures does not differ in any marked degree from that for the plain concrete columns. It would seem, then, that in general the position of the ends of the reinforcing rods has not affected the results in any marked manner, and there is no apparent reason for giving greater or less weight to the strength of any column. An exception to this may possibly be made in the case of No. 10, in which one bar rested on the plate and the failure was due to the breaking of the concrete around this rod at the end of the column. The condition is a severe one, and it is quite possible that the results in this case should be thrown out.

The average stress taken by the concrete, based on the analysis heretofore given, is, as shown in Table 8, for all the reinforced concrete columns 1243 lb. per sq. in. and with No. 10 omit-

ted, 1290 lb. per sq. in. Omitting Column No. 10, the lowest value is 26% below the average, the highest value is 30% above the average, and the average variation is 16%. The average strength of the plain concrete columns is 1553 lb. per sq. in. The average strength of the reinforced concrete columns, based on gross area and without allowance for the steel, is 1746 lb. per sq. in. It will be seen that the stress taken by the concrete is, in the case of the reinforced columns, about 15% less than the strength of the plain columns, and that the total strength of the reinforced columns is considerably more than that of the plain columns. These results may not be representative, but at least they indicate that care should be taken not to use too high working stresses in columns reinforced in this way. The fact that the values of the initial modulus of elasticity average for the reinforced columns so closely to the average for the plain columns, is confirmatory of the correctness of the results. It may also be noted that the abscissa of the vertex of the parabola fitted to the reinforced columns is less than that for the plain columns. This fact is possibly connected with the explanation of the lower concrete stresses in the reinforced columns.

The columns having ties around the longitudinal rods show no greater strength than those without ties, and there is no difference apparent in the manner of failure. It is true that buckling of the rods occurred between the ties, but this buckling must have taken place after the concrete reached its maximum stress, judging from the stress-deformation diagrams. In fact, it may not be expected, from ordinary analysis, that ties placed at so great a distance apart will have a beneficial effect upon the strength of the columns.

22. *Watertown Arsenal Column Tests.*—Not many tests have been made on plain and reinforced concrete columns in a systematic way with a view of determining the relative amount of stress in the steel and concrete while under load. Many occasional or desultory tests have been made, but usually these furnish no basis for comparison. The only series made in the United States, known to the writer, which gives an opportunity for making a comparison with the tests here recorded, is the series made by the United States government at Watertown Arsenal and reported in Tests of Metals for 1904. The well known care and trustworthiness of the Watertown tests make it seem profitable to in-

clude here a summary of such of these tests as may be compared with the University of Illinois columns. The columns selected include all of those made with one grade of 1–2–4 concrete and tested at about the same age and include the numbers from 1579 to 1585. As only one column of plain concrete was tested and a single test may not be at all representative of the characteristics of a concrete, but little comparison between plain and reinforced columns may be made. The number of reinforced columns and the range of the reinforcement are such that the tests give a good opportunity to study the relative stresses taken by steel and concrete.

The concrete was made of one part Vulcanite cement, two parts sand ($\frac{1}{8}$-in. sieve), and four parts pebbles ($\frac{1}{2}$ to $1\frac{1}{2}$ in. in diameter) by volume. The concrete averaged about 145 lb. per cu. ft. in weight. The reinforcing rods at the corners were placed $1\frac{7}{8}$ in. from the faces of the column, and where more than four rods were used the remaining rods were placed symmetrically in the interior. A variety of forms of reinforcement was used. The rods were cut to exact length and always had a direct bearing upon the bearing plates of the testing machine. In the test, the load was released several times, generally ten or more, but at progressively increasing amounts, and never more than once from any given load. The age of the columns averaged about $3\frac{1}{2}$ months at time of test.

TABLE 10.

DATA ON WATERTOWN ARSENAL COLUMNS.

Average length of columns, 94 inches.

Col. No.	Dimensions in. x in.	Gross Area sq. in.	Reinforcement		Age at Test days
			Amount and Kind	per cent	
1579	12.58x12.60	158.5	8—$\frac{3}{4}$-in. Thacher bars	2.09	102
1580	12.60x12.51	157.6	4—$\frac{3}{4}$-in. Twisted bars	1.43	103
1581	12.60x12.67	159.6	4—$\frac{3}{4}$-in. Thacher bars	1.03	104
1582	12.68x12.60	159.8	4—$\frac{5}{8}$-in. Corrugated bars	0.97	106
1584	12.63x12.60	159.5	8—$\frac{5}{8}$-in. Corrugated bars	1.94	104
1585	12.60x12.50	157.5	8—$\frac{3}{4}$-in. Twisted bars	2.86	105
1583	12.66x12.59	159.4	None	0.00	107

Stress-deformation diagrams are given in Fig. 30 to 36 at the end of the text. As before, the deformations given are gross and not net or elastic deformations. The line for steel, line for initial modulus of elasticity, and point of maximum stress in concrete are used in the way already given for the University of Illinois tests. Points for the parabolic stress-deformation relation for one-sixth, one-fourth, one-half, and full abscissa are marked by crosses. It will be seen that these diagrams have the same general characteristics as the University of Illinois tests, and that the parabolic curve fits them very closely.

Table 10 gives general information on the amount and nature of the reinforcement and the age of test. Table 11 gives the initial modulus of elasticity, the abscissa of vertex of the stress-deformation parabola, and the maximum stress taken by the concrete alone, the last being based upon the method already used, wherein the steel is considered to take a stress corresponding to

TABLE 11.

WATERTOWN ARSENAL COLUMN TESTS.

Col. No.	Gauged Length inches	per cent Reinforcement	Initial Modulus of Elasticity lb. per sq. in.	Abscissa of Vertex of Parabola	Maximum Stress in Concrete lb. per sq. in. Calculated	Maximum Stress in Concrete lb. per sq. in. Observed	Maximum Stress on Gross Area lb. per sq. in.
1579	50	2.09	3 200 000	.0012	1950	1950	2760
1580	50	1.43	2 000 000	.0012	1200	1200	1990
1581	50	1.03	2 200 000	.0014	1540	1460	1990
1582	50	0.97	2 300 000	.0014	1600	1540	1250
1584	50	1.94	2 800 000	.0014	1960	1920	2830
1585	50	2.86	2 200 000	.0012	1330	1330	3160
1583	50	0.00	2 770 000	.0013	1800	1710	1710
Av.	......	......	2 500 000	.0013	1620	1590	2240

its deformation and the concrete the remainder of the load. In Table 9 are given observed stresses at four deformations and also stresses calculated for the same points from the parabolic stress-deformation relation.

The one plain concrete column has a higher modulus of elasticity than the average value found for the reinforced columns,

and its stress-deformation curve does not reach the vertex of the containing parabola. These differences and the variability of stiffness and strength found in the reinforced columns, as well as the well established variability of concrete, go to show that the result of this one test may not be taken as representative of the strength and stiffness of plain concrete columns in comparison with the reinforced columns, and general conclusions may not be drawn. The ultimate strength of this column is, however, somewhat higher than the average maximum stress in the concrete for the reinforced columns as determined from the line for steel.

The average maximum stress in the concrete, for the reinforced columns, determined from the line for steel is fairly uniform, the range being 23% below the average and 24% above. The strength and stiffness of these columns are somewhat higher than given by the University of Illinois tests, as might be expected from the greater age at test and the use of pebbles instead of limestone. The columns are evidently somewhat more uniform in their make-up. The agreement of the observed values with those calculated by the parabolic stress-deformation relation is close. The average maximum compressive stress taken by the concrete, including the result for the one plain column, is 1590 lb. per sq. in. In general, the results of the two series of column tests are quite similar.

A study of the results shows that there is no marked characteristic difference in either stiffness or strength for columns made with any special form of reinforcing bar or with any given amount of reinforcement. For leaner concrete, and hence greater porosity, the difference in the elastic limits of the bars may be expected to have an effect upon the results.

23. *Modulus of Elasticity.*—As has already been stated, there is a great diversity of usage in reference to modulus of elasticity. Some writers have fallen into the error of using a constant ratio between stress and deformation, and yet of considering the stress-deformation diagram a parabola. Whether the stress-deformation relation should be considered variable, or whether a straight-line relation may be held to serve well enough for the range used, depends upon the particular use or application to which the relation is to be put. In fact, generally the test of the method to be employed lies in the purpose and end to be served in the application. In beams having a small amount of reinforcement the use of a

constant modulus may be permissible. In beams having a large amount of reinforcement and in which the compressive strength of the concrete is the controlling element, a variable modulus may be preferable. In reinforced columns, it would seem that a variable modulus (curved stress-deformation diagram) should be used in discussing the relative loads finally taken by the concrete and by the steel. The same test applies to the use of gross or net (elastic) deformations. If one purpose in the use of the deformation is to determine (a), in the case of a reinforced column, the amount of the deformation in the longitudinal steel reinforcement and from this to calculate the stress in the steel, or (b), in a reinforced beam, the amount of change in a section and from this the position of the neutral axis and the resultimg stress in the steel, it seems clear that gross (total) deformation should be used and not net (elastic) deformation, if we consider that a plane section before bending remains a plane section after bending. The use of elastic deformations must be misleading in these cases.

Again, the method to be used in determining the stress-deformation relation for repetitive loading should be judged in the same way. For example, when a compression test piece (a beam gives a similar phenomenon) has had loads applied in continuously increasing amounts, the stress-deformation line will be a curve, as is shown for example in the diagrams for Columns No. 5 and 12 given in Fig. 7 and 8. If now the load be gradually released, the points found during release will approximate to a straight line running to the set point. If the load is reapplied, the points found on the return line are not far from the straight line, and the second application of the given load shows a deformation somewhat larger than the first. To say, because at the partial loads the values approximate to a straight-line relation, that therefore the corresponding constant modulus of elasticity should be used in calculations on beams and columns, is evidently erroneous reasoning, as will be shown in the succeeding paragraph.

The set indicated in this line of released and reapplied loading does not exist throughout the cross-section of a beam under repeated loadings, as might at first thought seem to be the case. A method of more general applicability is to determine the final deformation after repetition for each loading seriatum. Thus, if the loads are to be applied one hundred times, apply, say, 100 lb. per sq. in. one hundred times and note the final deformation; apply

500 lb. per sq. in. one hundred times and note the final deformation; apply 1,000 lb. per sq. in., etc. Fig. 11 gives some idea how these deformations will change under repetitions, the points obtained for the same number of repetitions being connected together. The final diagram (represented by the lower curve) will resemble the one for the initial application, especially in portions of the curve other than near the ultimate, though the exact position of this will depend upon the number of repetitions, the elas-

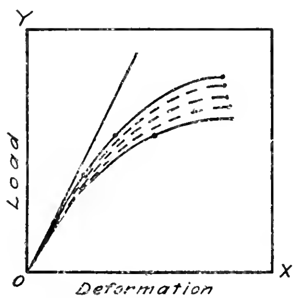


FIG. 11. DIAGRAM ILLUSTRATING EFFECT OF REPETITIVE LOADING.

ticity of the concrete, etc. Now, the same condition may be expected to exist in a beam that has been loaded one hundred times: at the remotest fiber the deformation is that due to repetition at the unit stress it has been subjected to, say 500 lb. per sq. in.; at a point half way to the neutral axis it is that due to repetition at one-half as great a unit stress, say 250 lb. per sq. in., and not (as would be the case if the results by the first mentioned method of loading were taken) the deformation under the condition that this fiber has been stressed to 500 lb. per sq. in. and then had had its stress reduced to 250 lb. per sq. in. This statement, of course, is approximate, since under the conditions described the position of the neutral axis would change, the stresses themselves would change, and the section itself would distort from a plane section, but nevertheless the illustration holds. The stress-deformation curve for repetitive loading should, then, be made by connecting points obtained under repetition of first one load, then a higher one, then still a higher one, etc. For a column, the deformations at intermediate loads are not so important, but the general character of the stress-deformation diagram is essential.

The use of both gross and elastic deformations contributes to the diversity of values for the modulus of elasticity of concrete given in engineering literature. Elastic deformations naturally give higher values. Caution should be used in accepting high values because they may have been obtained from elastic deformations or because they may have been taken from short specimens affected by the restraint of the bearing plates or because they may represent concrete of a much denser quality than is to be found under the conditions of practical construction. It is also to be seen, as shown in the preceding paragraph, (see also Fig. 11), that with repeated applications of a load the deformations will increase and the abscissa of the vertex of the assumed parabola will be larger. At the same time the maximum load which the concrete will take must be considered to be smaller. Under these two changes, it is evident that the resulting initial modulus of elasticity will be smaller than that for a single application of the load. What the amount of this decrease is will depend upon the nature of the concrete, its age and plasticity, and the number of repetitions of the load. The more plastic and porous the concrete, the greater the effect. The richer the mixture and the older the test piece, the less it will be. At the same time, it must be borne in mind that the concrete grows stiffer with age, and that most tests have been made at an early age, 30 to 90 days. Whether this increase in stiffness with time will counteract the decrease in value just noted, will depend upon the nature of the concrete and the number of applications. A similar effect may be expected in concrete by reason of its plastic nature when a load is applied for a considerable length of time (time effect), but little is known of this phenomenon.

It is noticeable that the values of the initial modulus of elasticity for the two series herein given agree fairly closely, an average of 2,250,000 lb. per sq. in. for 1–2–4 limestone concrete 60 days old tested at the University of Illinois, and an average of 2,500,000 lb. per sq. in. for 1–2–4 pebble concrete 105 days old tested at Watertown Arsenal. These values are based upon gross deformations and, in the main, first loading of the specimen. The combined effect of age and even moderate repetition, if the discussion in the previous paragraph holds, may be a modulus somewhat smaller than that given by these tests. What this modulus will become cannot be told without adequate tests. However, for

1–2–4 concrete of the quality used in the University of Illinois and the Watertown Arsenal columns (limestone in one, pebbles in the other), the initial modulus of elasticity at the age of a year and after a moderate number of applications of the load seems more likely to be below 2,500,000 lb. per sq. in. than above it. Further data on the effect of age of concrete and repetition of load upon modulus of elasticity are necessary before definite conclusions may be reached.

It should be noted that if a straight-line stress-deformation relation is to be used, particularly in the case of columns, the value chosen should be considerably less than that of the initial modulus of elasticity.

24. *Discussion of Basis for Working Stresses and Working Factor in Structures.*—The real basis for a working stress or a factor of safety to be used in designing seems not to be generally understood, or at least it is not often properly explained, and expressions sometimes heard indicate that the purpose and use of factor of safety and working stress are misinterpreted. Of course, no engineer will say that for a factor of safety of, say, four (using the term factor of safety as based upon the ultimate strength of the material) the structure will take four times the assumed load without injury. It is understood by engineers that the actual ratio of the load which the structure may properly take under the ordinary conditions of construction to the assumed load used in the calculations made in the design is not large and may, under some circumstances, not be very much above one. Yet the statement is sometimes made, or the inference may be drawn, that because a given working stress is to be used in the calculations there is no advantage in looking into the behavior of the material or the action of the structure at a stress higher than the assumed working stress. Before discussing further the meaning of the tests here recorded, it may be well to consider some of the aspects of working stresses and factors of safety.

Mild steel has a rather definite elastic limit and yield point beyond which the character of its action changes in a marked way. Beyond the yield point the rate of stretch in tension becomes almost at once one hundred or more times as much as it was within the elastic limit. In compression. the ultimate strength of mild steel is not far beyond its elastic limit.. It is evident that a structure made up of this material will distort and fail when a

load producing stresses not much greater than the elastic limit is placed upon it. The elastic limit of mild steel has a small range, its value running from 50% to 65% of the ultimate strength, depending upon the size of the piece, method of rolling, etc., and the steel is made under such conditions that little risk is taken in choosing a value for a particular size and shape of piece. The modulus of elasticity of steel is also quite uniform. It may be said then, that the properties of this material, with proper inspection, are fairly definitely known. When we base the factor of safety of a structure upon ultimate strength of mild steel, whether we do it consciously or unconsciously we have tacitly assumed that the factor of safety named in the calculations is nearly double the factor which will bring actual failure under the conditions assumed to exist in the structure.

For a plastic material, or a material not having a definite elastic limit, or at any rate one for which the stress varies directly as the deformation for at best only a small part of the ultimate strength of the material, a different consideration must be given. For such materials, the effect of lack of uniformity of the material, the effect of increased deformation, of repetitive loading, of time, and of other factors must be considered.

But there are other considerations which go to confine the working stress, particularly in concrete, to the low value usually assumed. Sometimes the stress is made low to allow for a possibly greater load than that assumed, or for a load applied other than statically. Even if the assumed load has the correct total amount, the following items may be said to influence the choice of a lower working stress: (1) Uneven distribution of load among members; (2) Unconsidered stresses due to settling, variability of the material, etc.; and (3) Variation in the material and in its fabrication.

(1) Even with a load of the amount assumed, the division of this load among the members of the structure may be uneven. Variations in stiffness, differences in quality of adjacent members due to inherent variations or to the variations which arise in such a material as concrete during fabrication and setting, differences due to restraint or lack of restraint at connections,—all go to make the actual distribution of the load different from its assumed division among the members. In a timber trestle bridge, the weaker stringer is generally less stiff than its stronger

neighbor, and hence the poor stringer takes a smaller share of the load and the good one a greater. Even in steel building construction, differences in rigidity of connections, modifications made to overcome lack of exact fit, and variations caused by field riveting act to modify the division of the load. In concrete construction the variations in fabrication and conditions of setting (e. g., in the beams and girders) and the consequent variable effect on stiffness and restraint may have a considerable effect upon the division of the load. This is especially true in the floor, beams, and girders, so that the load transmitted to a particular column may be quite different from that assumed.

(2) Settling of the foundation of one column more than of another is possible. A variation in the shrinkage of adjacent columns through variation in conditions attending fabrication or to a less extent in porosity or stiffness of column will modify the distribution of the load. Variations in size also affect this distribution. The more nearly uniform the dimensions and physical properties, the more nearly regular the division of load will be and the higher the allowable comparative working stress. In this respect, steel is an advantageous building material.

(3) The values of physical properties usually quoted are average values. The data were obtained from test pieces, sometimes large, frequently small, and these may be said to have been made and tested under favorable conditions. Since the members of a structure which have the poorest quality may have a controlling influence upon the amount of load to be carried, if average values are used the factor must be greater to allow for this. In other words, in poorly made beams or columns the load or stress which comes on the piece is relatively nearer the point of failure than is indicated by the use of the assumed working stress and an average ultimate value.

Enough has been said to show that the assumed stresses are not the actual stresses coming upon the members of a structure and that the relation between the assumed working stress and the average ultimate strength of the material is a matter which should involve thought and study. It may then be stated that (a) the stress actually brought upon a member of a structure by an assumed loading may be materially higher than the assumed working stress, and (b) the stress actually developed in a member may be much higher comparatively (i. e., with respect to its own ulti-

mate strength) than even this increased amount would indicate. This goes to show that the nature of the action of the material, including its stress-deformation relation, should be studied at points well above the assumed working stress. What point should be fixed upon as a basic point, upon which a working factor covering uneven distribution of load, uncertainty of quality, effect of repetitive loading, etc., may be based, will depend upon the nature of the material and the conditions of the structure. Some discussion of this subject will be given under Formulas for Plain and Reinforced Concrete Columns. No attempt will be made here to discuss what the working factor should be. Its value will depend upon many conditions which it will be impossible to discuss here.

25. *Formulas for Plain and Reinforced Concrete Columns.*—It seems hardly necessary to advance the idea here that for concrete columns used in ordinary building construction little attention need be given to the relation between length and lateral dimensions after a length of a few diameters has been reached. Text books on reinforced concrete contain long and complicated treatments involving Euler's relation and Rankine's formula. However, columns in buildings do not ordinarily go beyond, say, 12 or 15 diameters, and the ratio is usually much less, especially for the lower stories. Even for 15 diameters we may readily conclude from the calculated results of long column formulas and also from the small lateral deformation found in the columns tested that the difference in strength between a column 15 diameters long and one 5 diameters long is less than the variation among several columns of the same length. The same conclusion may be drawn from the set of tests of columns of varying length made at the Massachusetts Institute of Technology and quoted in Buel and Hill's Reinforced Concrete, page 76. For columns eccentrically loaded, the effect of any eccentricity is generally large in comparison with the lateral deflection used in the Euler analysis, and it may be said to be generally independent of the length of the column. Clearly, for conditions of ordinary design a formula for plain columns or for columns reinforced with longitudinal rods need not include the ratio of length to lateral dimension. In this discussion only concentric loading of columns is considered.

Obviously then, the formula for plain concrete columns is

$$P = Ac \qquad (3)$$

where P is the load assumed to be carried, A is the area of the column considered (in practice, part of the area at the outside, sometimes being excluded as a precaution in case of fire) and c is the working stress assumed or determined by other considerations.

In columns with longitudinal reinforcement, if we use P, A, and c as before, and denote by p the ratio which the area of the column bears to the area of the steel reinforcement, and by n the ratio between the stress existing in the steel and that in the concrete, the area of the steel will be pA, the unit-stress in the steel will be nc, and the area of the concrete will be $A(1-p)$. The total compressive stress in the steel will then be $pAnc$ and that in the concrete $Ac(1-p)$. The formula for the strength of the column may then be written

$$P=Ac(1-(n-1)p) \qquad (4)$$

This ratio is used rather than the ratio of the moduli of elasticity, since the latter may be misleading. If we call the area of the steel A, this formula may be put in the form,

$$P=(A+A'(n-1))c \qquad (5)$$

It will be necessary to select the value to be used for n in these formulas, and this will involve a discussion of the part of the stress-deformation field from which the basic value of the compressive strength used in the determination of the working strength is to be taken.

Granting that the actual stress in the member of a structure will probably be considerably greater than the stress calculated from the assumed distribution of the load, by reason of such agencies as have been discussed, and also that for members which are weaker than their neighbors the stress-deformation point developed will be relatively nearer the point of failure and hence farther up the diagram than the same stress will be in the diagram for an average test piece, and considering further that an additional allowance must be made for contingencies or emergencies, it is apparent that the field for this basic value of the compressive strength will be well along on the stress-deformation diagram. Obviously the extreme variability of concrete near the point of failure rules out values near the ultimate strength, even if other considerations do not. In all the field near the point of failure, too, the deformations are large, and repetition of loading increases them rapidly. The time effect of a permanent load is also large. It would seem that a stress greater than that which

gives a deformation equal to one-half of the ultimate deformation of the concrete, ($q=\frac{1}{2}$), is as large as may properly be taken as a basic value, even if the contingency of ever having such a stress in the member is very remote and then only temporary and not to be repeated. The stress corresponding to this deformation point is by the parabolic relation three-fourths of the ultimate strength of the concrete. This is not far from the basis adopted by Captain Sewell, eight-tenths of the ultimate strength, in his admirable paper on Reinforced Concrete Floor Systems in the Transactions of the American Society of Civil Engineers, Vol. 56. For many conditions of fabrication or of application of the load, a lower point in the diagram should be chosen, or the factor of safety increased. If we select the half-way point in the stress-deformation diagram ($q=\frac{1}{2}$ and $c=\frac{3}{4}c'$), for the basic value, the next step will be to choose the working factor, to cover the effect of repetition of stress, uncertainty of distribution of assumed load, variation in quality of material and construction, and other uncertainties and contingencies. It should be noted that this discussion is more particularly applicable to columns, since in beams with the amount of reinforcement ordinarily used the beam will fail through tension in the steel or by web stresses and not by compression of the concrete.

In the formula for reinforced concrete columns an important factor is the ratio of the stress in the steel to the stress in the concrete, called n in this discussion. This ratio is a variable one, depending upon the amount of deformation developed. To call it the ratio of the moduli of elasticity is indefinite and undesirable. If we assume the parabolic stress-deformation relation, it may be shown that this ratio is

$$n = \frac{1}{1-\frac{1}{2}q}\ \frac{E_s}{E_c} \qquad \text{(6)}$$

where E_s is the modulus of elasticity of the steel, E_c is the initial modulus of elasticity of the concrete, and q is the ratio of the deformation at the load under consideration to the ultimate deformation (vertex of the parabola). For low loads, n will not differ far from the ratio of the two moduli used above. At the four points noted on the stress-deformation diagrams it will be as follows: for $q=\frac{1}{6}$, $\frac{12}{11}$ times the initial ratio given above; for $q=\frac{1}{4}$, $\frac{8}{7}$ times the initial ratio; for $q=\frac{1}{2}$, $\frac{4}{3}$ times the initial ratio; and for

$q = 1, 2$ times the initial ratio. For $E_c = 2{,}500{,}000$, the initial value of n is 12, and it becomes 16 and 24 for the half-way deformation and the ultimate strength, respectively. For $E_c = 2{,}000{,}000$, the values of n for the same points are 15, 20, and 30. It is seen that n rapidly increases at the higher deformations.

Values of n have been determined from the observed deformations, counting the division of stress between the concrete and the steel to be according to the analysis heretofore given, and results for both the University of Illinois tests and the Watertown Arsenal data are given in Table 12. ϵ_c' represents the unit deformation at the point of maximum stress in the concrete (corresponding to abscissa of vertex of parabola). The same values are given in Fig. 12, the dots representing University of Illinois results and the crosses Watertown Arsenal values. The lines de-

TABLE 12.

RATIO OF STRESS IN STEEL TO STRESS IN CONCRETE.

VALUES OF n.

$\epsilon_c' =$ unit deformation at the maximum compressive stress in the concrete.

Col. No.	At 0	At $\frac{1}{6}\epsilon_c'$	At $\frac{1}{4}\epsilon_c'$	At $\frac{1}{2}\epsilon_c'$	At ϵ_c'	Remarks
1	11.7	12.2	13.7	16.0	24.8	U. of I. tests.
2	12.9	13.9	14.9	17.8	25.7	
3	12.8	13.2	14.2	17.4	26.4	
6	14.3	15.5	16.4	19.6	29.0	
7	11.7	13.1	13.7	15.5	23.8	
10	16.7	17.3	18.6	23.0	33.9	One rod on bearing plate.
11	12.3	12.3	13.4	16.2	24.7	
12	12.0	12.7	13.3	16.0	24.2	
14	15.0	14.8	16.5	20.0	29.4	Rods on plaster.
16	15.8	16.0	17.3	21.2	32.2	
17	15.8	20.4	20.0	20.1	27.2	
Av.	13.7	14.7	15.6	18.4	27.3	
1579	9.4	9.4	10.8	12.6	18.5	Watertown tests.
1580	15.0	17.5	17.5	19.6	29.2	
1581	13.6	15.4	15.9	18.4	28.1	
1582	13.1	16.0	15.9	17.9	25.6	
1584	10.7	11.4	12.7	14.9	21.4	
1585	13.6	16.5	16.8	19.0	27.1	
Av.	12.6	14.4	14.9	17.1	25.0	

note average values. In both Table 12 and Fig. 12, the value at the initial loading ($q=0$) is taken from the ratio for the initial modulus of elasticity for the column under consideration. It will be seen that the values range from 11.7 in one case for initial load to 34 in another at ultimate load.

If we assume that a concrete stronger than the average has a modulus of elasticity higher than the average, and that a weaker concrete has a smaller modulus, then the selection of a value of n higher than the average for use in design may be defended, for if a given column is made of concrete poorer than the average the steel by virtue of the low modulus of elasticity of the concrete in which it is embedded will have a greater stress thrown upon it than is indicated by an average value of n, and a column made better than the average will be capable of taking a greater load than that calculated with an average value of n. At least, it would seem logical to choose a value higher than the average

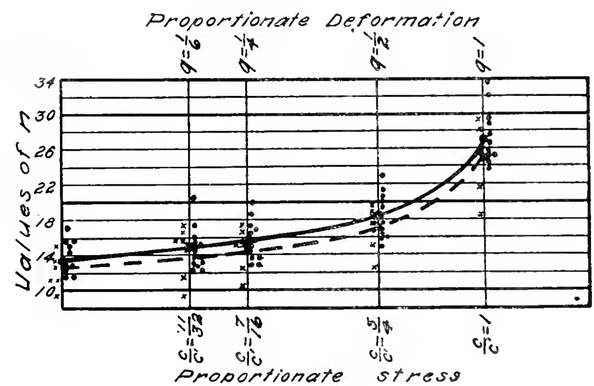


FIG. 12. VALUES OF n.

value rather than a lower value.

If we take the half-way deformation ($q=\frac{1}{2}$) as the point for determining our basic value for working factor and working stress, the average values of n in Table 12, 18.4 and 17.1, respectively, may serve as a guide for the value to be chosen for equation (4). For concrete of the character used in the tests, it would seem then, that 17 and 18 may be considered average values for n, and that values even higher than these, say, 18 to 21, may properly be selected.

It may be added that the value of n to be used for a given concrete will depend upon its density and stiffness. For a very rich concrete, not only will the initial modulus of elasticity be higher, but the deformation at maximum strength (abscissa of vertex of parabola) will be less. As a consequence of both of these changes the ratio n will be less for very rich concrete than for the test columns here considered. On the contrary, for lean concrete, the initial modulus of elasticity will be lower and the deformation at maximum stress higher, and therefore the ratio n will be higher than the values here given.

26. *Discussion of Columns in Building Construction*—It may be well to call attention to some of the reasons why columns may be a weak point in reinforced concrete construction and to offer a word of caution concerning their construction. The conditions of column construction as ordinarily carried on in building operations give little chance for efficient inspection, and there is abundant opportunity for great variation in the concrete, since the work is out of sight and the mixture of the material and the tamping or stirring will be far from uniform, much less uniform than in the test columns herein described. Even in test columns the poorer columns carried low ultimate loads. If, in addition to these considerations, the possible uneven distribution of the assumed load due to settlement, shrinkage, and uneven stiffness of the floor system be also taken into account, the need for using low working stresses and careful construction ought to be apparent. Evidently a fairly rich concrete made of a high grade of cement should be used. It is not improbable that in many buildings the working stresses used are too high for the concrete actually put into the columns. Besides, it must always be borne in mind that the strength obtained from test cubes may not be taken as representing the strength of a column. It is probable that many engineers have been misled by high values obtained on test cubes. Again, great caution should be used in the time allowance for removing the forms, particularly in cool weather, for the concrete in the olumns should be fairly well set before much of a load is allowed on it. A method of construction should be selected which will not bring weight upon the columns until the forms are removed, and the concrete is thoroughly set. It is fortunate that the concrete continues to gain in strength for a considerable time, although this advantage is counteracted in a structure to some extent by the injury to the concrete caused by early application of the load.

Both plain and reinforced concrete columns take up considerable room, particularly on the lower floors of a building. A richer concrete will permit a reduction in the area occupied. The large size of the columns makes the effect of eccentricity of loading smaller than it would be otherwise. Columns of hooped concrete have been used as a means of reducing the cross section. It is hoped that the investigation of hooped columns now in progress at the University of Illinois will throw some light on this allied subject.

27. *Summary.*—Parts of this discussion may be summarized as follows:

1. In discussions involving the strength and stiffness of concrete, the variability of the concrete must be taken into consideration. Test columns made with care to secure uniformity of conditions show considerable diversity in quality. An even greater variation in character must be expected under the conditions of ordinary building construction.

2. Cubes and other small test specimens are made under conditions which give a stronger and denser concrete than is generally found in full-sized pieces in building work. The restraining effect of the bearing plates of the testing machine also influences the results of cube tests. It is evident that the test pieces used in many tests recorded in engineering publications were made with a quality of materials, methods of fabrication, and conditions of setting which are far more favorable to high results than will be found under average conditions of construction. Caution should therefore be used in accepting as a basis for design values obtained from tests without knowing fully all the conditions accompanying the investigation.

3. The relative amount of load taken by the concrete and by the steel, in columns with longitudinal reinforcement, may be determined by means of the observed relation between loads and deformations under the assumption that the stress in the steel reinforcement is proportional to the deformation in the column. It is assumed that the bond between the steel and the concrete is adequate. This method forms an efficient means for discussing the relative stresses in steel and concrete.

4. By the method of analysis used, the average maximum stress in the concrete for the reinforced columns tested is found to be 15% less than the average for the plain concrete columns.

While this may not be taken as a final or representative conclusion, since it may be merely incidental to the columns used or the method of testing, it is at least an added reason for caution in choosing working stresses for this form of construction. The average total load taken by the reinforced columns, it should be understood, was considerably higher than the average for the unreinforced columns.

5. The plotted diagrams representing the loads or stresses in the columns and the corresponding deformations or shortenings, (stress-deformation diagrams), show a variable relation which is well expressed by the parabola. The tangent to the parabola at the point of zero load represents by its slope the initial modulus of elasticity of the concrete, and forms a convenient basis for an expression for the variable relation between stress and deformation. It should not be inferred that this relation is generally applicable to very rich or very lean concrete. The "Line for steel" in the diagrams for reinforced columns is helpful in determining the stress taken by the concrete and by the steel.

6. Gross (total) deformations and not net (elastic) deformations are used, since in the application of the stress-deformation relation to columns and beams gross deformations will, under the hypotheses ordinarily accepted, enable the stress in the steel to be determined, and net values will not.

7. The fact that during the operation of releasing a load the stress-deformation diagram does not follow the parabola but takes a course which approximates a straight line, is not a valid reason for not accepting the parabolic relation in the analysis of beam and column action. When a beam has been loaded up to a given load, the area of the part of a section above the neutral axis is in compression, and no point of this section has been strained beyond the amount then developed at that point, each point having the highest stress which has come upon it. The effect of repeating a load on a beam in progressively increasing amounts is to increase all the deformations in the section, but the resulting curve will still resemble the parabola, and the resulting initial modulus of elasticity will have a smaller value than that found for the first application of loads.

8. The Watertown Arsenal tests of columns of composition similar to the University of Illinois columns are comparable in strength and stiffness and in the form of stress-deformation

diagram and tend to confirm the results and conclusions of the University of Illinois tests. The average maximum compressive stress taken by the concrete in the Watertown Arsenal columns was 1590 lb. per sq. in. In the University of Illinois columns it was 1550 lb. per sq. in. for the plain columns and 1290 lb. per sq. in. for the reinforced columns.

9. The average value of the initial modulus of elasticity given for the University of Illinois columns, 2,250,000 lb. per sq. in., and that for the Watertown Arsenal columns, 2,500,000 lb. per sq. in., may be considered tentative values for 1–2–4 concrete of the kind described for use at an age of 60 to 105 days and first application of load. Age will increase the modulus and repetition decrease it. What the combined effect of these two agencies will be is not known, but it will vary with the conditions of materials and number of repetitions and also with the age at which loads are first applied. When a constant modulus of elasticity (straight-line relation) is used, the value chosen should be less than that for the initial modulus here given. The high values of modulus of elasticity frequently quoted are doubtless due to shortness of length of test piece, high quality in the test pieces used, use of elastic deformation, etc. The quality of the aggregate, as well as of the cement used in making test pieces, may not always be representative of that used in building operations.

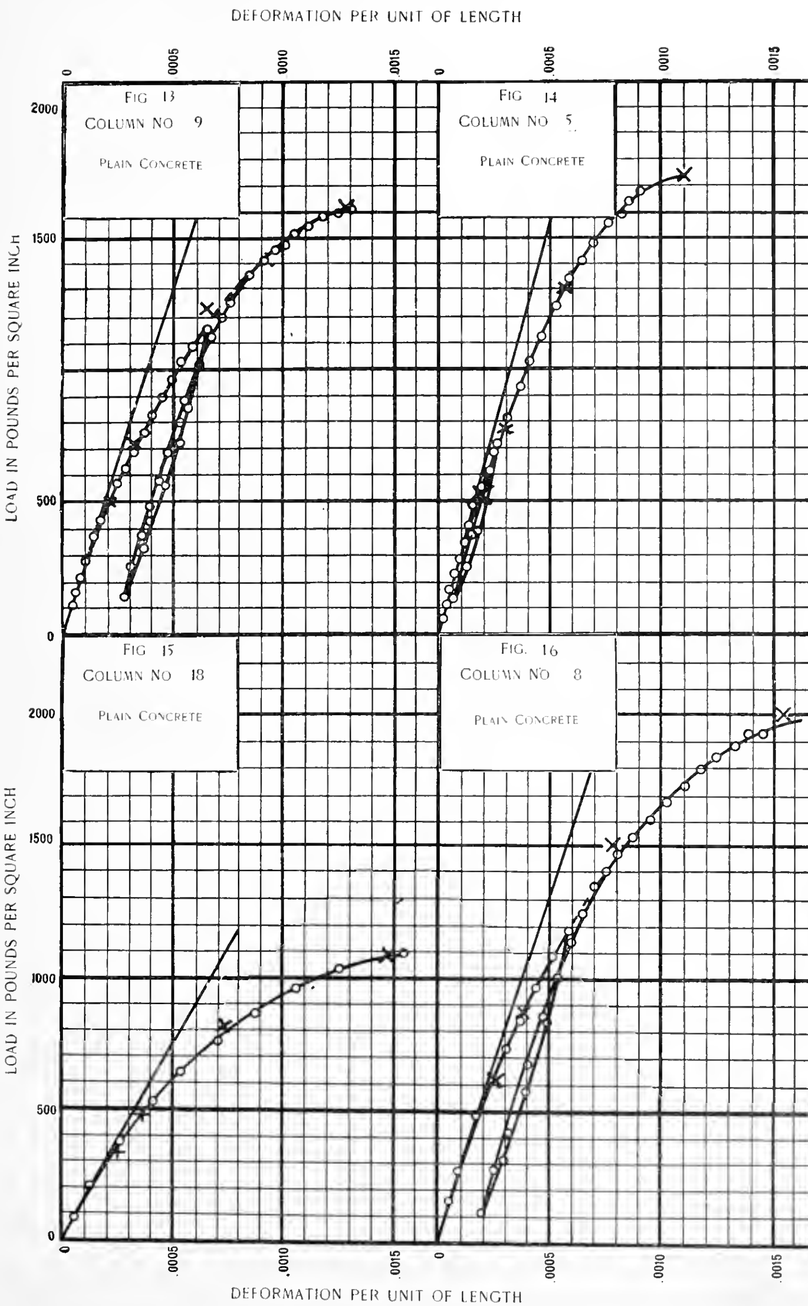
10. The proper basis for working factor and working stress for use in designing with any given material and form of construction is of much more importance than is usually given to it. The conditions of loading, of transmission and distribution of load, of variation in fabrication and construction, all act to make the stress actually developed in a member of a structure greater than the assumed working stress. For steel the real basic point is the elastic limit or yield point. For concrete this basic point may well be considerably below its ultimate strength. The choice of a value corresponding to a deformation equal to one-half of the deformation at point of failure is suggested. This, by the parabolic relation, is equal to three-fourths of the ultimate strength. Having selected a basic point, a working factor to obtain the working stress will then be chosen to cover contingencies and emergencies and the variations in distribution of load, quality of materials, method of fabrication, nature of load and its manner of application, etc. The range in the values for the working fac-

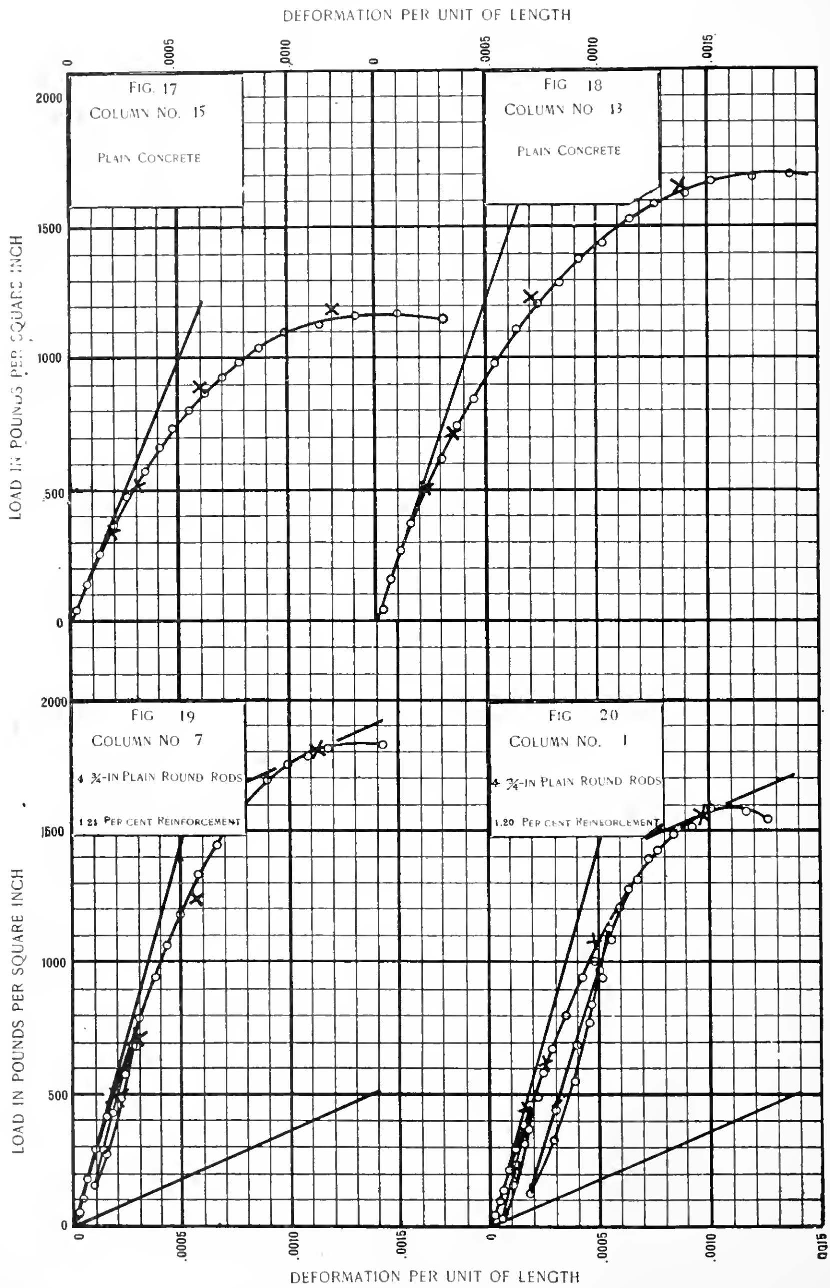
tor which may be used under the various conditions of repetition of load, workmanship and material, is of course much greater with concrete than will be necessary with such a material as mild steel.

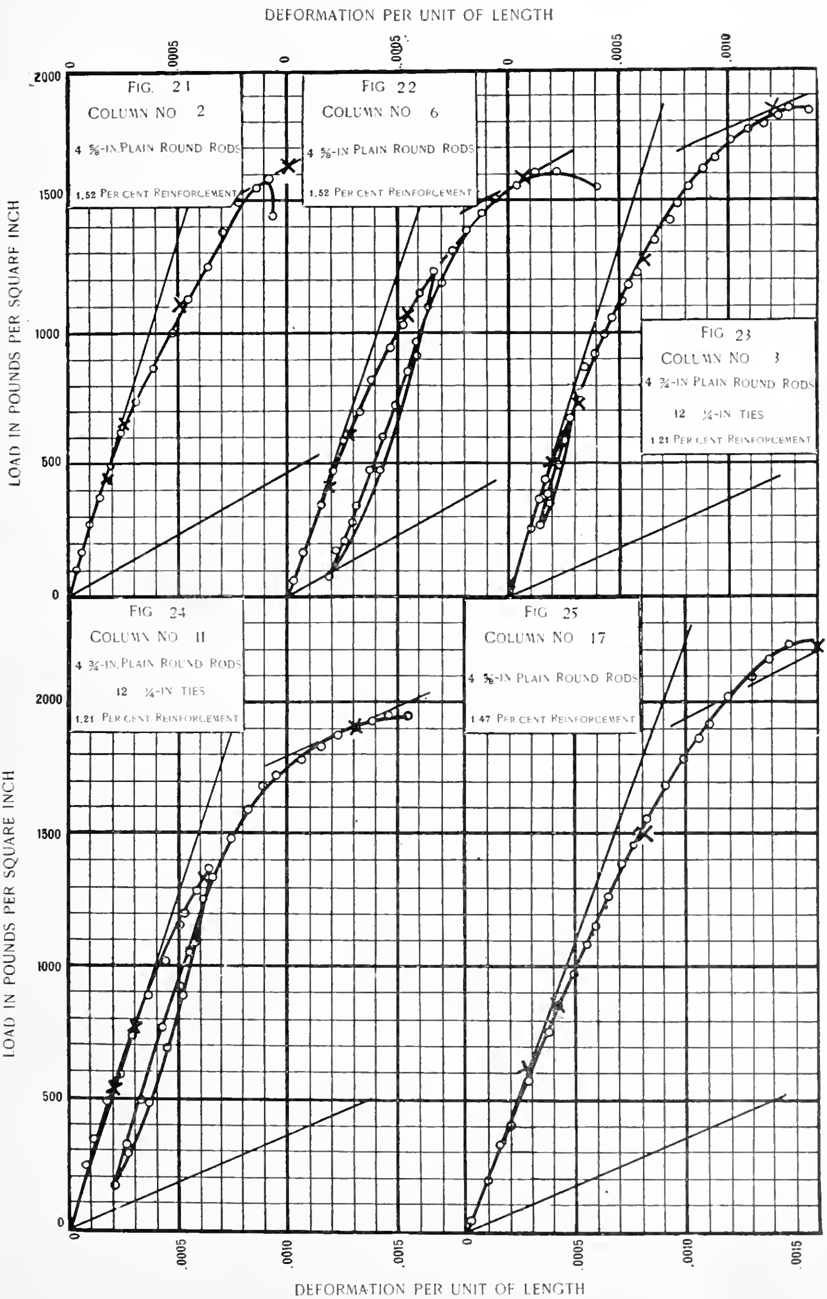
11. The ratio between the amount of stress taken by the steel and that taken by the concrete in columns reinforced with longitudinal rods varies as the load is increased, as may be expected from the variable stress-deformation relation of the concrete. In these tests this ratio varied from 12 at the initial application of the load in one column to 34 at the maximum strength of the concrete in another. For the average initial modulus of elasticity of the concrete, the range is from $13\frac{1}{3}$ at the zero load to $26\frac{2}{3}$ at the ultimate. For very rich concrete the effect of the additional stiffness and the lower final deformation is to decrease the ratio n, and for lean concrete the smaller modulus and greater final deformation will make it larger.

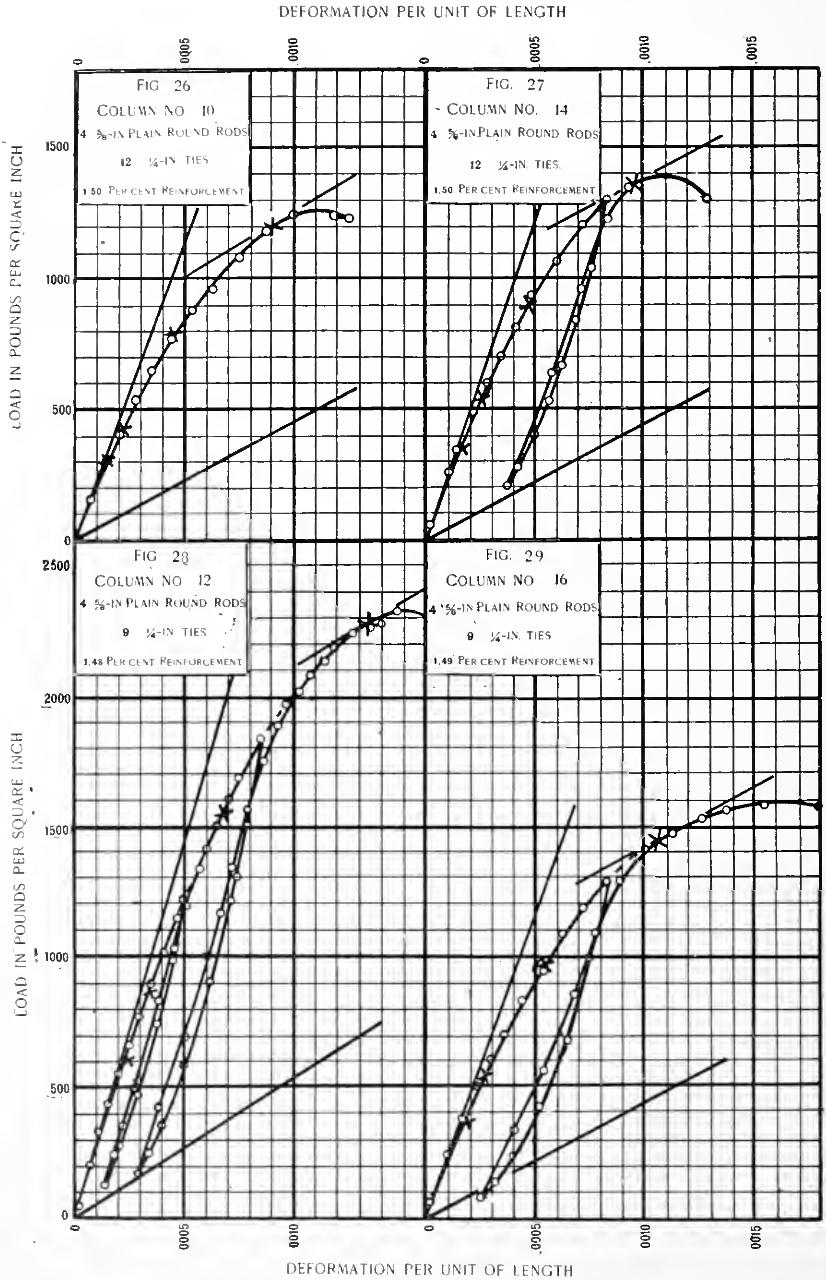
12. If we choose the half-way deformation for our basic point, the value for the ratio of stress in steel to stress in concrete may, from the two sets of experiments, be taken as 17 to 18 for 1–2–4 concrete of the quality used in the tests. However, this ratio may properly be taken to be even higher than an average value, since for columns weaker than the average column the ratio may be expected to be higher than the average value and hence to fit the conditions of such columns better, while for columns stronger than the average the added strength of the concrete will go to make up for the overestimated stress in the steel. For this assumption, 18 to 21 may be used.

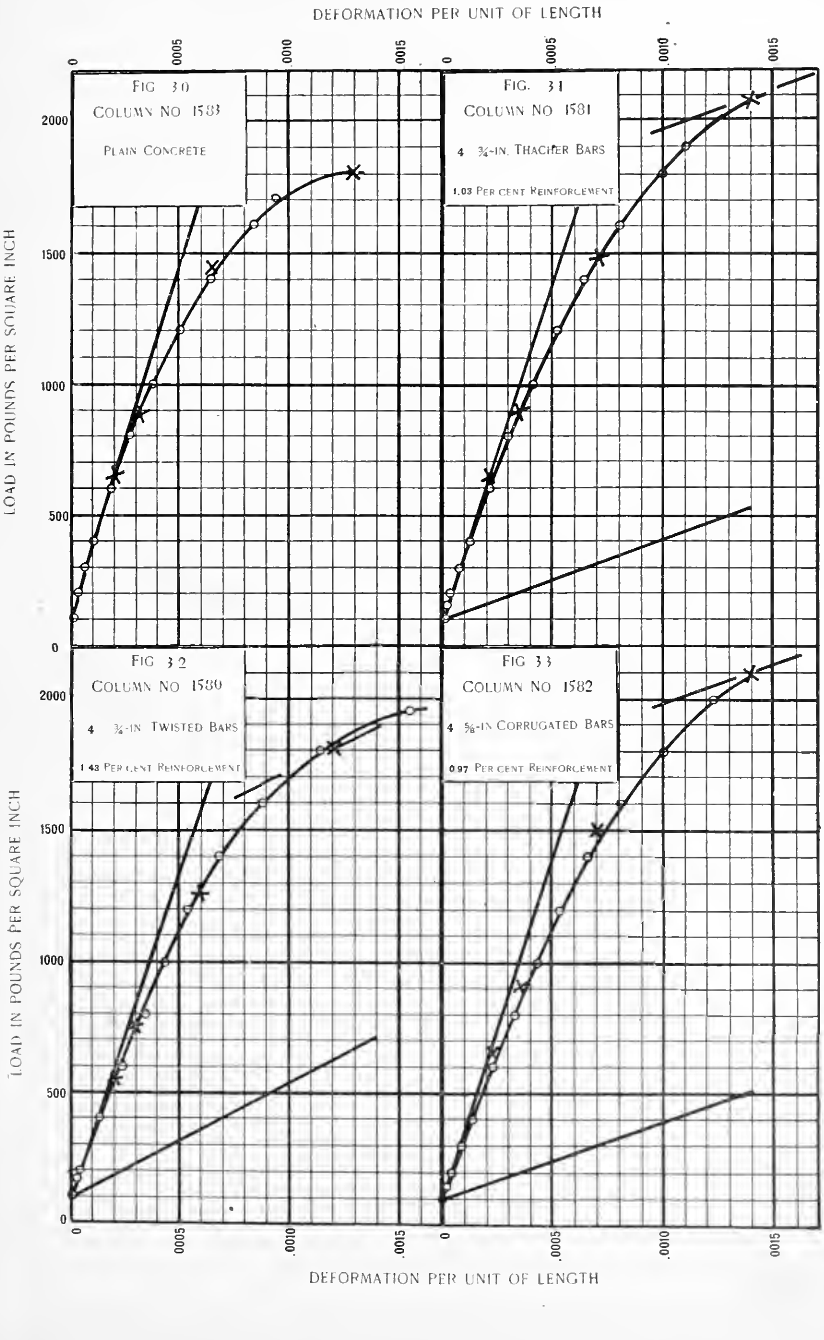
13. Under the conditions of building construction, columns may form a weak element in the structure. To overcome this, the working stresses should be kept low and every precaution taken to secure proper materials, workmanlike fabrication, and efficient inspection.


DEFORMATION PER UNIT OF LENGTH
0
.0005
.0010
.0015
FIG 13
COLUMN NO 9
PLAIN CONCRETE
FIG 14
COLUMN NO 5
PLAIN CONCRETE
FIG 15
COLUMN NO 18
PLAIN CONCRETE
FIG. 16
COLUMN NO 8
PLAIN CONCRETE
LOAD IN POUNDS PER SQUARE INCH
2000
1500
1000
500
0
DEFORMATION PER UNIT OF LENGTH


DEFORMATION PER UNIT OF LENGTH
FIG. 17
COLUMN NO. 15
PLAIN CONCRETE
FIG. 18
COLUMN NO. 13
PLAIN CONCRETE
FIG. 19
COLUMN NO. 7
4 ¾-IN PLAIN ROUND RODS
1.21 PER CENT REINFORCEMENT
FIG. 20
COLUMN NO. 1
4 ¾-IN PLAIN ROUND RODS
1.20 PER CENT REINFORCEMENT
LOAD IN POUNDS PER SQUARE INCH
DEFORMATION PER UNIT OF LENGTH


DEFORMATION PER UNIT OF LENGTH
FIG. 21
COLUMN NO 2
4 5/8-IN. PLAIN ROUND RODS
1.52 PER CENT REINFORCEMENT
FIG 22
COLUMN NO 6
4 5/8-IN PLAIN ROUND RODS
1.52 PER CENT REINFORCEMENT
FIG 23
COLUMN NO 3
4 3/4-IN PLAIN ROUND RODS
12 1/4-IN TIES
1.21 PER CENT REINFORCEMENT
FIG 24
COLUMN NO 11
4 3/4-IN. PLAIN ROUND RODS
12 1/4-IN TIES
1.21 PER CENT REINFORCEMENT
FIG 25
COLUMN NO 17
4 5/8-IN PLAIN ROUND RODS
1.47 PER CENT REINFORCEMENT
LOAD IN POUNDS PER SQUARE INCH
LOAD IN POUNDS PER SQUARE INCH
DEFORMATION PER UNIT OF LENGTH


DEFORMATION PER UNIT OF LENGTH
FIG. 26
COLUMN NO. 10
4 5/8-IN. PLAIN ROUND RODS
12 1/4-IN. TIES
1.50 PER CENT REINFORCEMENT
FIG. 27
COLUMN NO. 14
4 5/8-IN. PLAIN ROUND RODS
12 1/4-IN. TIES
1.50 PER CENT REINFORCEMENT
FIG. 28
COLUMN NO. 12
4 5/8-IN. PLAIN ROUND RODS
9 1/4-IN. TIES
1.48 PER CENT REINFORCEMENT
FIG. 29
COLUMN NO. 16
4 5/8-IN. PLAIN ROUND RODS
9 1/4-IN. TIES
1.49 PER CENT REINFORCEMENT
LOAD IN POUNDS PER SQUARE INCH
DEFORMATION PER UNIT OF LENGTH


DEFORMATION PER UNIT OF LENGTH
0
.0005
.0010
.0015
FIG 30
COLUMN NO 1583
PLAIN CONCRETE
FIG. 31
COLUMN NO 1581
4 ¾-IN. THACHER BARS
1.03 PER CENT REINFORCEMENT
FIG 32
COLUMN NO 1580
4 ¾-IN TWISTED BARS
1.43 PER CENT REINFORCEMENT
FIG 33
COLUMN NO 1582
4 ⅝-IN CORRUGATED BARS
0.97 PER CENT REINFORCEMENT
LOAD IN POUNDS PER SQUARE INCH
0
500
1000
1500
2000
DEFORMATION PER UNIT OF LENGTH

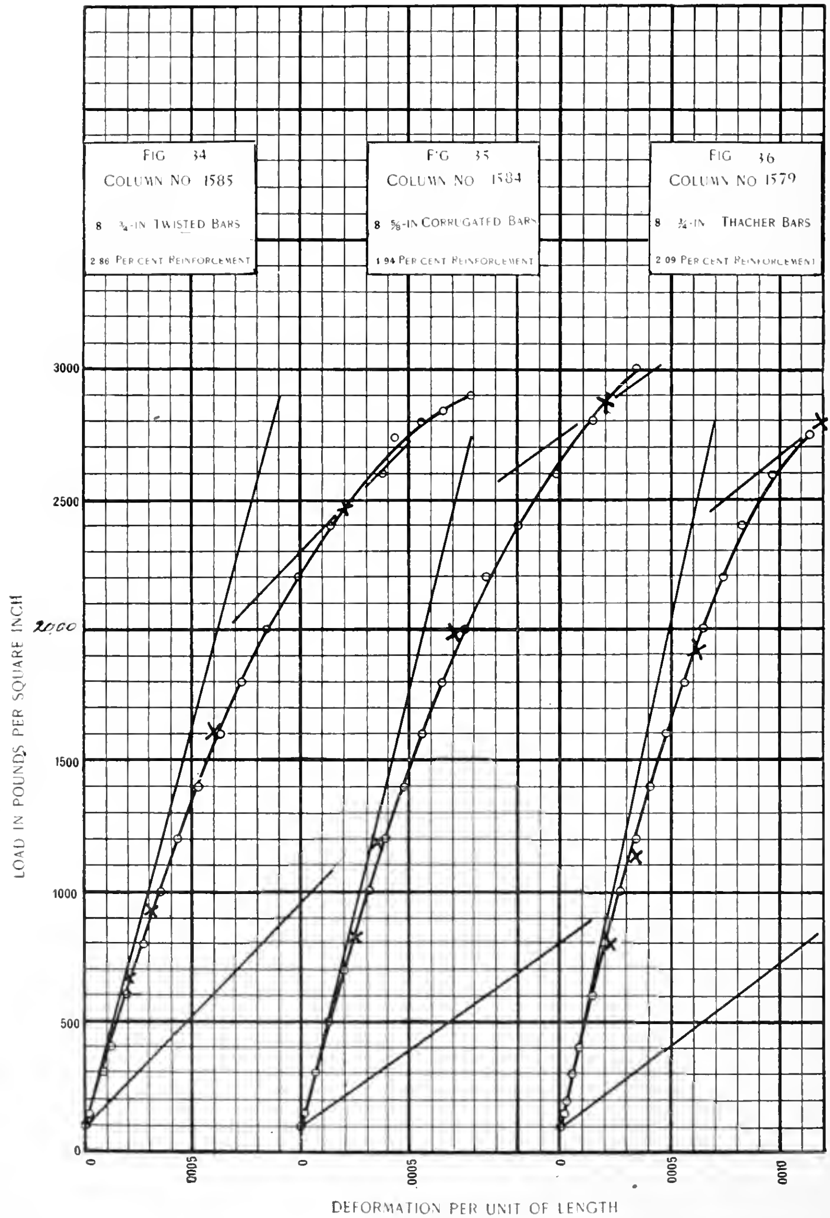


FIG 34
COLUMN NO 1585
8 ¾-IN TWISTED BARS
2.86 PER CENT REINFORCEMENT
FIG 35
COLUMN NO 1584
8 ⅝-IN CORRUGATED BARS
1.94 PER CENT REINFORCEMENT
FIG 36
COLUMN NO 1579
8 ¾-IN THACHER BARS
2.09 PER CENT REINFORCEMENT
LOAD IN POUNDS PER SQUARE INCH
3000
2500
2000
1500
1000
500
0
0
.0005
0
.0005
0
.0005
.0010
DEFORMATION PER UNIT OF LENGTH

Publications of The Engineering Experiment Station

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.

Circular No. 1. High Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

Bulletin No. 10. Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. (In press).

Bulletin No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 11 APRIL 1907

EFFECT OF SCALE ON THE TRANSMISSION OF HEAT THROUGH LOCOMOTIVE BOILER TUBES

BY EDWARD C. SCHMIDT, M. E., ASSOCIATE PROFESSOR OF RAILWAY ENGINEERING, AND
JOHN M. SNODGRASS, B. S., INSTRUCTOR IN RAILWAY ENGINEERING

During the past twenty or thirty years there has been considerable discussion in railroad circles as to the effect of scale upon the heat-transmitting properties of tube surfaces, and the consequent effect upon the consumption of fuel. Statements as to the extent to which deposits of scale affect the conductivity of a tube or sheet have been made from time to time and have differed widely.

In a committee report on boiler incrustation in the Proceedings of the American Railway Master Mechanics Association of 1872, we find the following quotation from a paper by Dr. Joseph G. Rodgers before the American Association for the Advancement of Science, given as the best information which the committee had been able to obtain: "The evil effects of scale are due to the fact that it is relatively a non-conductor of heat. Its conducting power compared with that of iron is as 1 to 37.5. This known, it is readily appreciated that more fuel is required to heat water through scale and iron than through iron alone. It has been demonstrated that a scale $\frac{1}{16}$ in. thick requires the extra expenditure of 15% more fuel. As the scale thickens the ratio increases. Thus when it is $\frac{1}{4}$ in. thick, 60% more is required: . . . ."

The report continues as follows: "On most western roads incrustations will form to a thickness of from $\frac{1}{4}$ in. to $\frac{3}{16}$ in. in the course of one year, and will increase at a still greater ratio as long as the engine is kept in service. Thus after four months' time, there will have accumulated in our engines nearly $\frac{1}{16}$ in. of scale. If Dr. Rodgers' theory be correct, after one month's service our engines will consume $3\frac{1}{4}\%$ more fuel than at first; after two months' service $7\frac{1}{2}\%$ and so on, making an average for the year of over 20% more fuel than they would have consumed if using pure water."

In a report before the same Society in the year 1877 upon "Feed Water" a committee under the sub-heading, "The Effect of Incrustations on the Consumption of Fuel," reports in part as follows: "The increase in the consumption of fuel, on account of incrustations on the heating surfaces of boilers, varies with the thickness and density of the deposit. When porous the water will penetrate it, but when hard and compact it presents a complete barrier to the contact of the water with the heating surfaces. As incrustations are poor conductors of heat, an increased consumption of fuel is inevitable where they exist." The committee then cites a number of cases for which sufficient data were collected to estimate the per cent loss that was occasioned due to scale deposits. A table showing the average miles run to one ton of coal by engines upon the Illinois Central Railroad for three months prior to and for three months after the removal of incrustations, including 120 such cases and extending over a period of three years, showed as a general average an increase of 11% in the consumption of coal for three months prior to the cleaning of the boilers, as compared with the three months immediately succeeding. The result of 11% loss due to scale is, of course, entirely a general result, as individual cases often showed less miles run per ton of coal after cleaning than before. This difference from the general result could in most cases be accounted for by weather differences. A second case is cited for two passenger engines, which were of the same size and pattern, and which were run with the same trains on alternate days. Records were kept for the six months preceding and six months following the cleaning of the boilers. Both engines had previously been cleaned at the same time and had made an average of 34,047 miles before the test began. The tests as run showed a difference in favor of clean

heating surfaces of 17.5%. Mr. Wells, the master mechanic making this test, however, concludes, on account of the scaled tubes being run more often during the winter months than the cleaned tubes, that of the 17.5% difference in consumption of fuel between clean and incrusted heating surfaces about 2% was due to temperature and 15½% to the effects of incrustation. Similar tests with two freight engines gave a difference of 26% in favor of clean heating surfaces. A correction of 4% was applied to this on account of different atmospheric temperatures under which the tests were made, "thus giving a net saving of 22% in favor of clean boilers on two freight engines."

Other cases might be mentioned giving results more or less similar, also cases in which little or no loss was found to be occasioned by the presence of scale. Likewise, the opinion has been not uncommonly expressed that there is either no fuel loss due to the presence of scale in the usual amounts or that loss is so small as to be of little practical importance.

During the last few years there have been made by the Railway Engineering department of the University of Illinois four series of experiments to determine the relative conductivities for heat of clean and scale-covered locomotive boiler heating surfaces. A fifth series of tests is now being carried on along the same general lines as the others. It is the purpose of this bulletin to report upon the results of the first four series of these tests.

The tests were planned with the purpose of determining, not only the actual transmission loss due to scale in individual cases, but also the relation of this loss to the scale thickness. The last three series were arranged especially to try to determine whether there is any regularity of variation of heat transmission loss with scale thickness and to study at the same time the effects of chemical composition on this loss.

It was recognized from the outset that in any series of comparative tests for the purpose of determining the loss in heat transmission due to the presence of scale, practically exact similarity of conditions was essential for trustworthy results. A study of previous work done along this line, such as the cases and results already referred to, also served to emphasize the necessity of such care. In all of the work hereinafter reported the greatest stress has been laid upon this point, i. e. the elimination of variations in conditions except the scale itself. The difficulties

which have been encountered while prosecuting this work have still further emphasized this necessity. The difficulties attending road-testing are well understood both as to exact measurements and similarity of conditions. These considerations were of weight in determining that the tests herein reported should be largely of laboratory character rather than road tests.

The first series* of tests was made during May and June 1898. The method employed in making the tests was as follows:—

A Mogul freight locomotive, which had been in service 21 months and which was about to be sent to the shops for repairs and new tubes, was set in the roundhouse and the boiler tested by the standard method. The locomotive was then sent to the shops and the boiler carefully cleaned and retubed. All the scale was removed and samples analyzed from nine different parts of the boiler. It was then sent back and again tested for evaporation under the same conditions as before cleaning. Before making the trials with the clean tubes the locomotive was allowed to make one or two trips on the road so as to insure its being thoroughly clean. The tests were made in the round-house at Champaign, Illinois.

The locomotive was set in the roundhouse over a pit and the tender removed. A car of coal was then run in back of the engine and on this were arranged the scales for weighing the coal. All of the feed water was weighed and then delivered into a tank placed on a platform by the side of the car, and connected with the suction pipe of the injector.

The slide valve on one side of the locomotive was moved back far enough, by disconnecting the valve rod, so that the steam generated could pass directly into the exhaust, and thus out through the nozzle and produce the necessary draft as usual. A 2-in. pipe was also run from the dome to the atmosphere, a valve in the pipe furnishing additional means of disposing of the steam generated. The tests were started by the standard method, i. e., raising steam to the running pressure, drawing the fire and starting with weighed wood.

At the end of the tests the ashes were all weighed. One of the regular road firemen fired for all the tests and the boiler and furnace were operated under the usual road conditions. A series of observations was made during these tests, to determine the re-

*This test constituted the thesis for graduation of Messrs. F. H. Armstrong and J. N. Herwig.

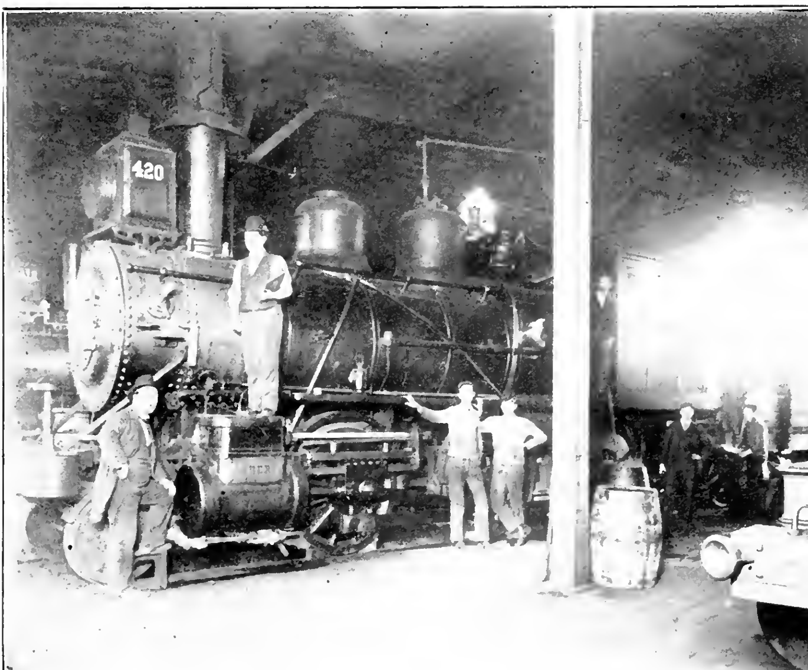


Fig. No. 1   Locomotive No. 420

lation between the blast-pipe pressures and vacuum in smoke box and furnace, as well as the velocity of the gases in the stack at various points along two diameters at right angles to each other. The locomotive upon which the tests were made was a Mogul freight engine made by the Rogers Locomotive Works, and was one of nineteen in use at that time on the Chicago division of the Illinois Central Railroad between Champaign and Centralia, Illinois. Fig. 1 shows the arrangements just described and gives a general view of the locomotive.

Leading dimensions:	
No. of Locomotive	420
Diameter of cylinder	19 in.
Stroke	26 in.
Diameter of drivers	$56\frac{1}{2}$ in.
Weight on drivers	106,400 lbs.
Weight on trucks	19,600 lbs.
Total weight of engine	126,000 lbs.
Diameter of boiler	62 in.
Number of tubes	236
Diameter of tubes	2 in.
Length of tubes	11 ft. 1 in. over tube sheets
Length of firebox	$114\frac{1}{8}$ in.
Width of firebox	$33\frac{3}{8}$ in.
Depth of firebox, front end	$67\frac{7}{8}$ in.
Depth of firebox, back end	$59\frac{7}{8}$ in.
Length of grate	$114\frac{1}{8}$ in.
Width of grate	$33\frac{3}{8}$ in.
Diameter of dry pipe	8 in. outside
Diameter of steam dome	$29\frac{1}{8}$ in. inside
Height of steam dome	28 in.
Kind of lagging	Magnesia sectional
Governing proportions:	
Grate area	26.45 sq. ft.
Total heating surface	1531.6 sq. ft.
Area of draft through tubes	573.5 sq. in.
Ratio of grate to heating surface	57.9
Fuel used:	
Commercial name	Odin
Commercial size	Mine run
Lumps per cent	75
Small coal per cent	20
Slack per cent	5
Heat units per lb. of dry coal (by calorimeter)	12,240

The results of these tests are exhibited in the accompanying tables.

TABLE 1

LOG OF OBSERVATIONS GIVING AVERAGE VALUES

LOCOMOTIVE NO. 420 ILLINOIS CENTRAL RAILROAD

	First Series Scale in Boiler		Second Series Cleaned Boiler	
Date of Trial (1898)	May 2	May 3	May 31	June 1
Duration of trial, hours	8.33	8.17	8.03	8.16
Steam pressure by gage	143	140	116.40	114
Vacuum in smoke box (in. of water)	2	2	2.9	2.8
Temperature of roundhouse (degrees F.)	72	62	79	89
Temperature of feed water in tank (degrees F.)	57	54	58.5	59.4
Temperature of escaping gases (degrees F.)	623	670	621	687
Temperature of steam (degrees F.)	362	360	348	346
Moisture in coal, per cent	4.0	4.0	4.0	4.0
Percentage of ash (from ash pan)	15.6	15 6	16.6	18.7
Percentage of moisture in steam	2.25	2.25	2.85	2.85

TABLE 2

RESULTS OF EVAPORATION TEST OF LOCOMOTIVE BOILER
ENGINE NO. 420, ILLINOIS CENTRAL RAILROAD

First Series: After running 21 months and accumulating a scale deposit $\frac{1}{32}$ to $\frac{3}{64}$ inch thick.

Second Series: After cleaning and putting in new tubes.

		First Series Scale in Boiler			Second Series Clean Boiler		
	Date of Trial (1898)	May 2	May 3	Mean	May 31	June 1	Mean
		lbs.	lbs.	lbs.	lbs.	lbs.	lbs.
Evaporative Performance	Water actually evaporated per lb. of dry coal	5.21	5.27	5.24	5.81	5.85	5.83
	Equivalent water from and at 212° F. per lb. of dry coal	6.29	6.39	6.34	6.99	7.04	7.01
	Water actually evaporated per lb. of combustible	6.17	6.25	6.21	6.95	7.16	7.05
	Equivalent water from and at 212° F. per lb. of combustible	7.46	7.59	7.53	8.36	8.61	8.48
Rate of Combustion	Dry coal burned per hour per sq. ft. of grate surface	57.45	58.51	57.95	59.80	60.00	59.90
	Per sq. ft. of tube opening	394.80	402.10	398.40	411.00	412.80	411.90
	Per sq. ft. of water heating surface	.93	.95	.94	.97	.98	.97
Rate of Evaporation	Water evaporated per hour from and at 212° F. per sq. ft. of grate surface	361.80	374.40	368.10	418.00	416.00	417.00
	Per sq. ft. of tube opening	2486.00	2573.00	2529.00	2874.00	2857.00	2865.00
	Per sq. ft. of water heating surface	5.89	6.09	5.99	6.81	6.76	6.79

The loss due to scale in this boiler was (7.01 minus 6.34) divided by 7.01 or 9.55 %.

The water used in the locomotive tested was taken from tanks at Centralia, Kinmundy, Little Effingham, Neoga, Dorans, Galton and Champaign. From the thickness of scale deposited during the 21 months it is evident that these waters are comparatively good for this section of the country.

The average thickness of the scale on the principal heating surfaces was $\frac{3}{64}$ in. The total weight of scale removed on cleaning was 485 lbs. The boiler had been in regular service during the 21 months.

The locomotive was cleaned and retubed at the Burnside shops of the Illinois Central Railroad. When the boiler was opened all the scale removed was carefully weighed, the scale on the tubes being determined by weighing the tubes before and after cleaning them. The scale from the shell and firebox sheets that could be removed was carefully collected. The total weight of scale was as follows:—

Weight of scale from flues........	360 lbs.
Weight of scale from shell............	125 lbs.
Total weight of scale..............	485 lbs.

At nine different points in the boiler the thickness of the scale was determined by the average of many measurements, and samples were secured for analysis as follows:—

Point 1. Near injector discharge, hard and soft scale $\frac{1}{8}$ in. thick.
2. On upper tubes, hard smooth scale uniform thickness $\frac{1}{32}$ in.
3. On lower tubes, hard scale near middle, $\frac{1}{16}$ in. thick.
4. Mud covering hard scale at No. 3, $\frac{3}{32}$ in. thick.
5. Scale from side sheet, flue sheet, and tubes rough and scaly.
6. From bottom of barrel, 4 ft. from flue sheet.
7. On crown stays, 3 in. to 6 in. from crown sheet.
8. On crown sheet, rivet heads and base of stays.
9. From stay bolts at water line.

The results of the analyses of these scales calculated to compounds are shown in Table 3.

TABLE 3

RESULTS OF THE ANALYSES OF BOILER SCALE FROM ENGINE NO. 420

SCALE CONSTITUENTS CALCULATED TO COMPOUNDS AND EXPRESSED IN PER CENT

Point No.	Silica SiO_2	Iron and Aluminum Oxides Fe_2O_3 and Al_2O_3	Calcium Sulphate $CaSO_4$	Calcium Carbonate $CaCO_3$	Calcium Oxide CaO	Magnesium Carbonate $MgCO_3$	Magnesium Oxide MgO	Organic Matter and Undetermined
1	7.70	3.20	10.86	65.81	....		9.55	2.78
2	25.20	7.10	16.45	20.92	....	3.05	19.52	7.67
3	8.00	4.99	21.22	48.90	1.90	....	4.48	10.51
4	7.84	3 27	4.38	61.17	....	8.14	5.47	9.73
5	15.89	4.30	21.38	30.36	....	8.71	7.66	11.70
6	11.25	7.70	1.97	67.08	....	....	9.29	2.71
7	18.25	6.90	1.95	45.51	5.69	....	16.77	4.93
8	13.05	7.85	40.03	24.33	1.14	....	9.12	4.48
9	22.70	12.75	11.73	28.32	....	5.86	18.45	0.11

The loss, as found by these trials, due to the presence of scale, was 9.55 % of the fuel.

EXPERIMENTS WITH SINGLE TUBES

The last three series of experiments to determine the loss due to scale have been laboratory experiments entirely. They were made during the years 1901, 1904 and 1905, and are referred to as the series of 1901, 1904 and 1905 respectively.*

The locomotive boiler tubes upon which the experiments were made in 1901 were furnished by the Peoria and Eastern division of the Cleveland, Cincinnati, Chicago and St. Louis, the Illinois Central, the Chicago, Burlington and Quincy, and the Chicago, Milwaukee and St. Paul Railways. The tubes used in 1904 and 1905 were furnished by the first two railroad companies mentioned above. Table No. 4 gives information concerning these tubes. Fig. 2 shows some of the tubes tested.

*These experiments were conducted by the following men as theses for graduation: Series of 1901, by F. L. McCune; Series of 1904, by W. A. Miskimen and C. N. Stone; Series of 1905, by H. F. Godeke and A. A. Hale.

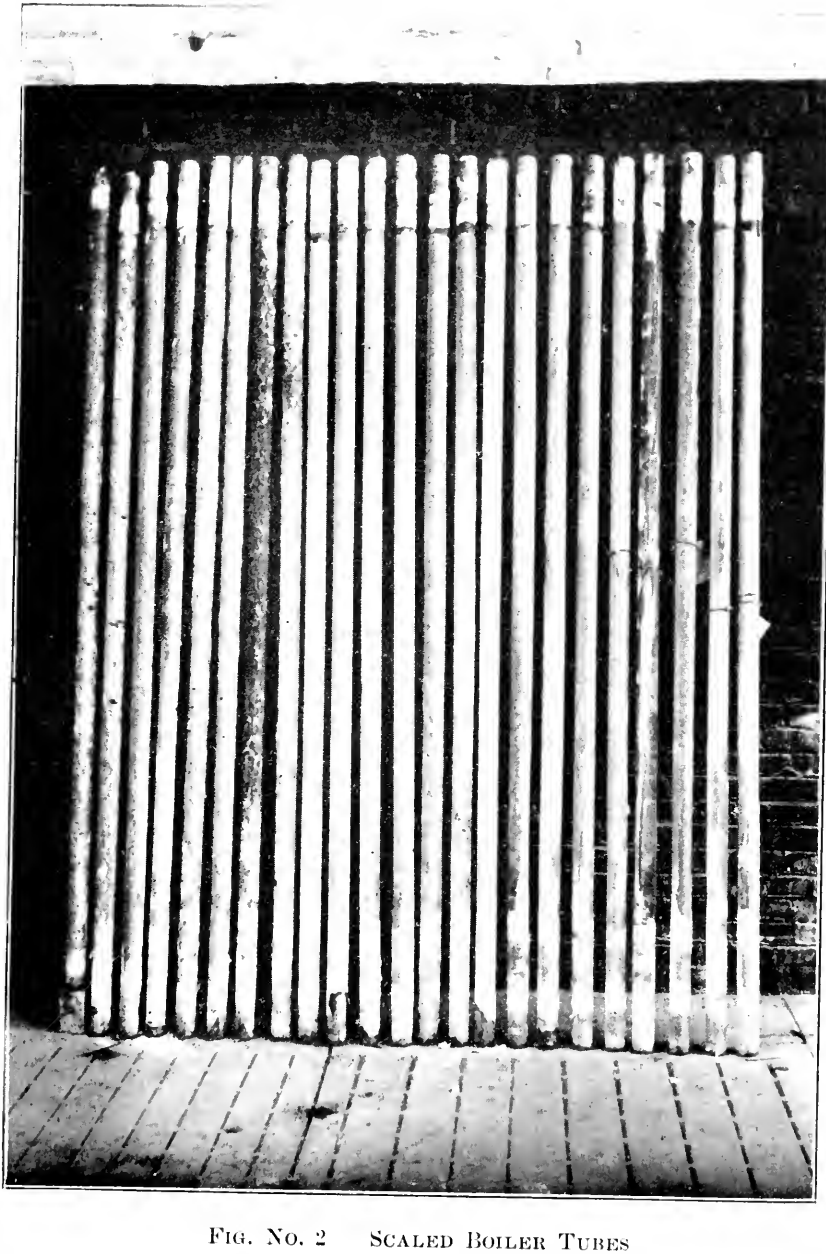


Fig. No. 2 Scaled Boiler Tubes

TABLE 4

THE TRANSMISSION OF HEAT THROUGH SCALE-COVERED BOILER TUBES
RAILWAY ENGINEERING DEPARTMENT—UNIVERSITY OF ILLINOIS

Tube Number	Furnished by	No. of Engine from which Tube was taken	Length of time in service Months	Outside Diameter of Tube Inches	Average Thickness of Scale Inches	REMARKS General Character of Scale, Etc.
1	2	3	4	5	6	7
						SERIES OF 1901
1	I. C. R. R.	311	10.5	2	0.06	Even, hard, dense
2	P. & E. RY.	526	13.5	2	0.04	Soft, porous. Removed in places
3	P. & E. RY.	536	5.5	2	0.02	Hard, dense, white
4	C. M. & ST. P.	126	....	2	0.03	Hard, dense, white
5	C. M. & ST. P.	1337	....	2	0.13	Hard, dense
6	I. C. R. R.	820	5.5	2	0.07	Mileage during service, 19690
7	P. & E. RY.	513	37.5	2	0.04	Hard, dense, rough, one end. Soft, porous at the other
9	C. B. & Q.	1179	....	2	0.11	Hard, porous, gray. Mileage, 50889
11	I. C. R. R.	1107	21	2	0.09	Soft, porous
14	P. & E. RY.	....	....	2	....	New and clean tube
						SERIES OF 1904
1	I. C. R. R.	41	16	2	0.04	Hard, gray. In bad condition
2	I. C. R. R.	41	16	2	0.07	Loose, gray
3	I. C. R. R.	41	16	2	0.08	Loose, gray
4	I. C. R. R.	141	15	2	0.05	White, porous. Removed in places
5	I. C. R. R.	141	15	2	0.04	White, porous. Removed in places
6	I. C. R. R.	141	15	2	0.08	White, porous
7a	C.C.C. & ST. L.	540	..	2	0.06	White, soft, irregular
7b	C.C.C. & ST. L.	540	..	2	0.06	White, soft, irregular
8a	C.C.C. & ST. L.	540	..	2	0.05	Hard, white, irregular
8b	C.C.C. & ST. L.	540	..	2	0.04	Hard, white
9	I. C. R. R.		..	2	0.06	Hard
10	I. C. R. R.	440	..	2	0.03	Hard, gray
11	I. C. R. R.	440	..	2	0.09	Gray, porous
12	I. C. R. R.	440	..	2	0.03	Gray, porous
13	I. C. R. R.	...	..	2	....	Clean tube
						SERIES OF 1905
3	I. C. R. R.	136	18	2	0.07	Medium
4	I. C. R. R.	802	8	2	0.05	Hard
8	C.C.C. & ST. L.	533	10	2	0.03	Soft
9	C.C.C. & ST. L.	233	14	2	0.09	Very soft
10	I. C. R. R.	1424	10	2	0.07	Soft
11	C.C.C. & ST. L.	233	14	2	0.04	Very soft
12	I. C. R. R.	140	21	2	0.07	Hard
13	I. C. R. R.	303	18	2	0.02	Hard
14	I. C. R. R.	1004	21	2	0.01	Medium
15	I. C. R. R.	1012	12	2	0.03	Very hard
7	....	....	..	2	....	Clean tube

These tests were made as laboratory tests on account of the desire to make comparative tests under entirely similar conditions except in regard to the scale itself and in order that more exact measurements might be made than were found possible with road or roundhouse tests. The apparatus used in all of these tests has been practically the same from year to year. It is shown in Fig. 3, 4, and 5 and consists of a long water chamber through which the tube to be tested was passed, and in which water was circulated. On one end of this water chamber was fastened a combustion chamber, at the forward end of which was placed a burner. This burner was supplied with gas and air. Combustion took place in the chamber, which served the purpose of the firebox. The hot gases passed through the boiler tube to the air. The water entered the water chamber at the right, leaving it at the left as indicated in Fig. 3, at both of which points its temperature was read upon the thermometers there shown. The water tank received the water from the city mains. It was provided with an overflow, as shown, and the water was led directly down from the bottom of this tank to the water chamber. This was used in order to give a constant pressure at the inlet and thus to avoid variations in the rate of flow of the water. The gas and air tanks were arranged to give constant pressures of gas and air. The inner vessels, open at the bottom, float in water contained in the outer tank and confine the air or gas in the space above the water level. These inner tanks can be weighted at will to give any desired pressure to the air or gas contained within them.

During the tests of 1901 a copper ball pyrometer was employed to obtain the temperatures of the gases entering the tube being tested. For the series of 1904 and 1905 a Le Chatelier pyrometer was employed for this purpose. The location of the pyrometer is shown in Fig. 3. The temperature of the gases as they left the flue was read on the thermometer shown at the end of the tube.

The purpose of the tests was to measure the number of heat units transmitted per hour through the different tubes. This was accomplished by weighing the water which circulated around the tube in the water chamber and measuring its rise in temperature. The attempt was made to maintain a constant furnace temperature at the entrance to the tubes throughout all experiments of each

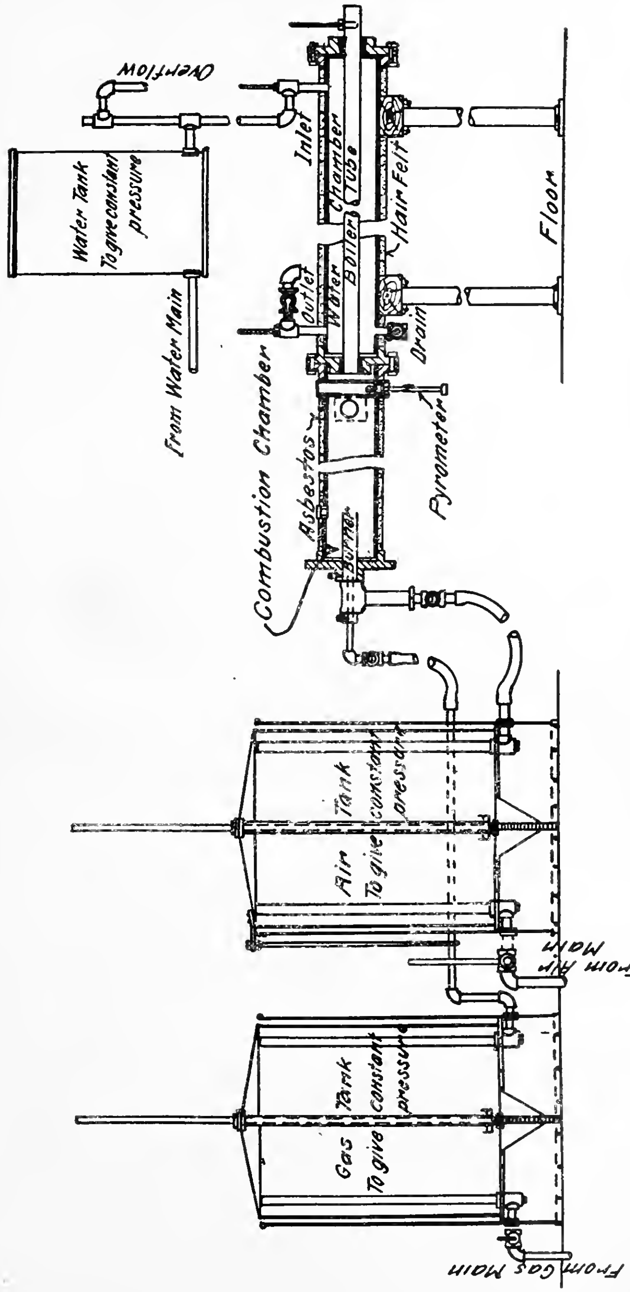


FIG. NO. 3 APPARATUS FOR THE DETERMINATION OF THE EFFECT OF SCALE ON HEAT TRANSMISSION THROUGH TUBES

series and thereby have available for transmission the same amount of heat, since the amounts of gas and air supplied to the burner were continually the same.

TABLE 5

THE TRANSMISSION OF HEAT THROUGH SCALE COVERED BOILER TUBES

RAILWAY ENGINEERING DEPARTMENT UNIVERSITY OF ILLINOIS

			Average Temperatures During Tests Degrees Fahr.											
			Of Furnace Gases			Of Circulating Water								
Tube Number	Test Number	Duration of Test—Hours	In Combustion Chamber	Of Escaping Gases	Average Temperature of Gases	At The Inlet	At The Outlet	Average Temperature of Water	Rise in Temperature of Water	Weight of Water Used During Test—In Pounds	Difference Between Temperature of Water and Temperature of Gases—"Range of Temperature"—Column 6 Minus Column 9	B. T. U. Transmitted Through Tube During Test	B. T. U. Which Would Have Been Transmitted Had The Range Of Temperature Been The Same As For Clean Tubes	Decrease in Conductivity Due to Scale Per Cent Loss
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SERIES OF 1901														
1	11	1	1657	256	957	66.9	112.7	89.8	45.8	651.3	867.2	29830	30063	*0.6
1	12	1	1702	252	977	66.8	112.6	89.7	45.8	643.3	887.3	29463	29021	2.9
2	16	1	1650	260	955	65.0	113.9	89.5	48.9	526.5	865.5	25746	25999	13 0
2	18	1	1631	269	950	64.1	110.3	87.2	46.2	581.0	862.8	26981	27331	8.5
3	1	1	1693	239	966	61.7	110.4	87.6	45.7	593.5	878 4	27123	26987	9.7
3	2	1	1690	238	961	65.7	111.0	88.4	45.3	600.7	875.6	27212	27162	9 1
4	20	1	1639	259	949	67.1	111.2	89.2	44.1	676.0	859.8	29812	30301	*1.4
4	21	1	1622	252	937	66.8	109.7	88.3	42.9	713.5	848.7	30609	31522	*5.5
5	6	1	1559	248	904	65.9	110.6	88.3	44.7	583.0	815.7	26060	27923	6.5
5	22	1	1702	265	984	63.9	109 3	87.1	45.1	621.0	896.9	28330	27606	7.6
6	3	1	1682	265	974	65.3	110.4	87.9	45 1	685.5	886.1	30916	30494	*2.1
6	23	1	1718	284	1001	63.6	110.7	87.2	47.1	616.0	913.8	30427	29101	2.6
7	8	1	1695	252	974	67.1	113.3	90.2	46.2	612.0	883.8	28274	27961	6.4
7	9	1	1693	256	975	66.9	112.0	89.5	45.1	669.5	885.5	30194	29802	0.2
9	4	1	1535	249	892	65.3	109.9	87.6	44.6	546.0	804.4	24351	26459	11.4
9	15	1	1597	252	925	65.8	110.9	88.4	45.1	505.0	836.6	22776	23794	20.4
11	7	1	1659	262	961	63.9	110.0	87.0	46.1	589.3	874 0	27167	27167	9.1
11	24	1	1683	271	977	64.1	109.5	86.8	45.1	590.5	890.2	26809	26321	11.9
14	5	1	1595	266	931	61.0	109.1	86.7	45.4	611.0	844.3	29238	Clean	
14	13	1	1690	267	979	67.8	114.0	90.9	46.2	650.2	888.1	30039	Tubes	
14	14	1	1693	268	981	68.5	114.2	91.4	45.7	661 0	889.6	30315	*Increase	
Average			1659	267	961	66.8	112.5	89.7	45 8	652.7	874.0	29874		

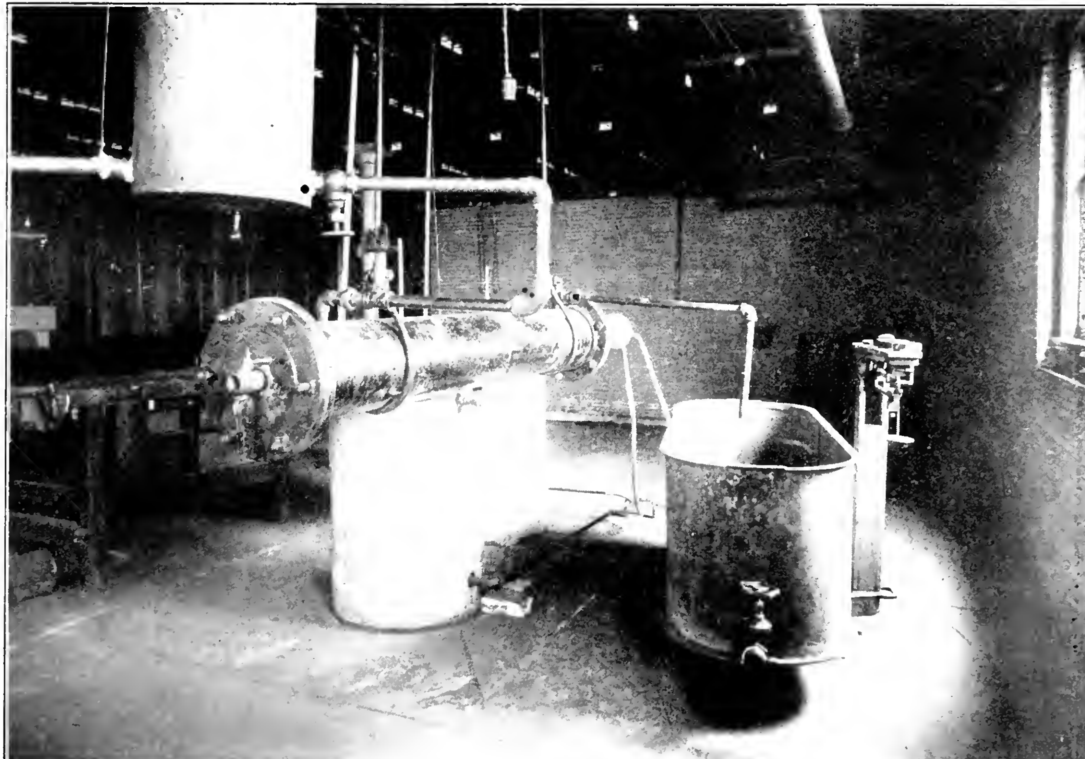


Fig. No. 4 Apparatus for the Determination of the Effect of Scale on Heat Transmission Through Tubes

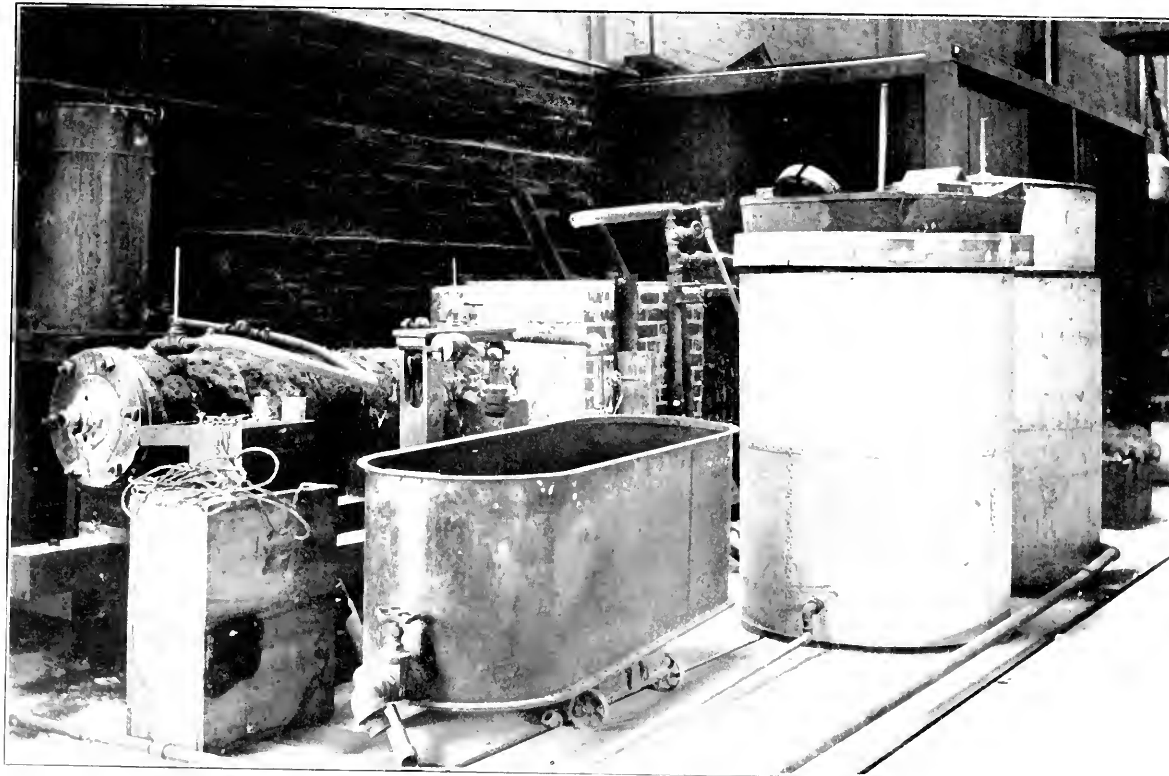


Fig. No. 5 Apparatus for the Determination of the Effect of Scale on Heat Transmission Through Tubes

SERIES OF 1904

1	15	1	1432	648	1040	56.8	84.7	70.8	27.9	829	969.2	23129	22227	5.1
2	16	1	1439	659	1049	57.9	84.0	71.0	26.1	850	978.0	22185	21128	9.8
3	17	1	1436	667	1052	58.0	83.2	70.6	25.2	895	981.4	22554	21405	8.6
4	18	1	1418	515	967	57.7	80.4	69.1	22.7	975	897.9	22133	22958	2.0
5	19	1	1438	523	981	57.1	83.4	70.3	26.3	814	910.7	21408	21895	6.5
6	20	1	1439	511	975	58.3	82.7	70.5	24.4	865	904.5	21106	21734	7.2
7a	13	1	1439	647	1043	57.0	81.9	69.5	24.9	875	973.5	21788	20845	11.0
7b	14	1	1437	523	980	56.5	81.5	69.0	25.0	803	911.0	20075	20525	12.4
8a	12	1	1443	623	1033	57.0	89.4	73.2	32.4	662	959.8	21449	20812	11.1
8b	11	1	1414	593	1004	58.9	91.3	75.1	32.4	654	928.9	21190	21247	9.3
9	10	1	1423	547	985	57.6	83.8	70.7	26.2	767	914.3	20095	20471	12.6
10	7	1	1431	517	974	59.1	84.8	72.0	25.7	808	902.0	20766	21442	8.5
11	8	1	1415	536	976	58.8	85.1	72.0	26.3	735	904.0	19331	19916	15.0
12	9	1	1426	551	989	59.0	82.9	71.0	23.9	896	918.0	21414	21727	7.2
13a	6	1	1441	554	998	56.5	82.5	69.5	26.0	891.	928.5	23166	Clean Tubes	
13b	5	1	1439	563	1001	56.7	85.1	70.9	28.4	825.	930.1	23430		
13c	4	1	1440	569	1005	56.3	82.6	69.5	26.3	900.	935.5	23670		
Average			1440	563	1001	56.5	83.4	70.0	26.9	872.	931.4	23422		

SERIES OF 1905

3	48	1	1783	873	1328	62.4	103.6	83.0	41.2	717	1245.0	29540	28722	2.8
3	49	1	1781	879	1330	62.4	102.1	82.3	39.7	753	1247.7	29894	29002	1.9
3	50	1	1798	867	1333	62.0	99.2	80.6	37.2	800	1252.4	29760	28764	2.7
4	45	1	1816	733	1275	62.2	102.6	82.4	40.4	699	1192.6	28240	28663	3.0
4	46	1	1809	715	1262	63.2	102.0	82.6	38.8	707	1179.4	27432	28155	4.8
4	47	1	1806	705	1256	63.3	102.4	82.9	39.1	692	1173.1	27057	27920	5.6
8	24	1	1788	740	1264	59.7	102.7	81.7	43.0	641	1182.3	27563	28220	4.5
8	25	1	1790	743	1267	60.1	102.4	81.3	42.3	660	1185.7	27918	28502	3.6
8	26	1	1805	743	1274	60.1	101.7	80.9	41.6	656	1193.1	27290	27688	6.3
9	27	1	1752	791	1272	59.9	101.1	80.5	41.2	683	1191.5	28140	28588	3.3
9	28	1	1753	800	1277	60.0	100.6	80.3	40.6	682	1196.7	27690	28009	5.2
9	29	1	1763	793	1278	59.7	100.6	80.2	40.9	695	1197.8	28126	28727	2.8
10	30	1	1772	786	1279	59.0	101.2	80.1	42.2	674	1198.9	28443	28718	2.9
10	31	1	1782	788	1285	58.8	101.8	80.3	43.0	663	1204.7	28509	28646	3.1
10	32	1	1783	792	1288	59.1	101.4	80.3	42.3	671	1207.7	28383	28449	3.8
11	34	1	1776	805	1291	67.1	103.1	85.1	36.0	767	1205.9	27612	27717	6.2
11	35	1	1785	803	1294	67.0	102.4	84.7	35.4	753	1209.7	26656	26674	9.8
12	37	1	1776	804	1290	64.5	102.1	83.3	37.6	747	1206.7	28087	28176	4.7
12	38	1	1785	790	1288	64.0	102.1	83.1	38.1	721	1204.9	27470	27598	6.6
13	39	1	1766	740	1253	60.2	101.4	80.8	41.2	679	1172.2	27975	28889	2.3
13	40	1	1754	748	1251	60.7	102.9	81.8	42.2	668	1169.2	28190	29190	1.3
13	41	1	1747	736	1242	61.2	101.5	81.4	40.3	695	1160.6	28009	29213	1.2
14	43	1	1805	808	1307	58.5	102.1	80.3	43.6	657	1226.7	28645	28267	4.4
14	44	1	1792	803	1298	58.8	102.9	80.9	44.1	645	1217.1	28445	28290	4.3
15	51	1	1804	759	1282	61.1	102.1	81.6	41.0	688	1200.4	28208	28445	3.8
15	52	1	1808	736	1272	60.8	100.9	80.9	40.1	701	1191.1	28110	28568	3.4
7	21	1	1792	794	1293	64.5	102.1	83.3	37.6	782	1209.7	29403	Clean Tubes	
7	22	1	1796	787	1292	64.2	103.6	83.9	39.4	754	1208.1	29708		
7	23	1	1808	784	1296	63.3	101.4	82.4	38.1	776	1213.6	29566		
Average			1799	788	1294	64.0	102.4	83.2	38.4	770.7	1210.5	29559		

The method of conducting a test was as follows:

The burner was first lighted and the gas and air pressures adjusted, then the flow of water through the water chamber was regulated and the apparatus allowed to run until all conditions had become uniform. This usually occupied about one hour, at the end of which time the test was started.

At the beginning of a test for the series of 1901 a determination of temperature was made by the copper ball pyrometer and readings were taken on all three thermometers, which readings were also taken at intervals of five minutes throughout the test. At the end another determination was made of the furnace temperature, and the water which had flowed through the chamber was weighed.

Observations for the tests of 1904 and 1905 were taken in a similar manner except that all temperature readings including that of the furnace were taken at regular intervals of 10 minutes.

Table No. 5 gives a summary of the data of the various tests and also the calculated results. The furnace temperature was not maintained quite the same throughout the tests, as an inspection of Table No. 5 will show. It was likewise impossible to maintain the average temperature of the circulating water the same during all the tests. Consequently the range of temperature between the gases in the tube and the water varied somewhat. Since the rate of transmission of heat through the tube varies directly with this range in temperature it is necessary, in order to compare the conductivity of the different tubes, to reduce the actual amounts of heat transmitted to what they would have been for one standard range of temperature. This standard range was assumed the same as the range existing during the test of a new clean tube, such a tube being tested with each series of tests.

These derived figures are given in column 14, Table No. 5, and they show the amounts of heat which would have been transmitted in each case had the difference between the temperature of the gases and the temperature of the water been the same in all tests of that particular series, i. e., the same as during the tests of the clean tube then tested. It is from the figures in this column that the losses due to scale are computed. This loss expressed as a per cent is exhibited in column 15 of Table No. 5.

Table No. 6 gives the chemical analyses of the scale found upon the tubes tested in the series of 1901, 1904 and 1905. The constituents of the scale are calculated to compounds and expressed as per cent. These analyses were made by the Chemical department of the University of Illinois.

TABLE 6

THE TRANSMISSION OF HEAT THROUGH SCALE-COVERED BOILER TUBES
RAILWAY ENGINEERING DEPARTMENT—UNIVERSITY OF ILLINOIS

CHEMICAL ANALYSES OF SCALE

Tube Number	Constituents of Scale — Amount in per cent								
	SiO_2	Fe_2O_3 Al_2O_3	$CaSO_4$	$CaCO_3$	CaO	$MgCO_3$	MgO		
	Silica	Oxides of Iron and Aluminum	Calcium Sulphate	Calcium Carbonate	Calcium Oxide	Magnesium Carbonate	Magnesium Oxide	Moisture	Organic Matter and Alkali
1	2	3	4	5	6	7	8	9	10
				SERIES OF 1901					
1	7.00	8.32	16.78	47.16	....	1.30	11.20	1.18	7.06
2	5.68	8.98	27.30	22.27	10.45	....	15.82	1.14	8.34
3	9.24	10.98	2.04	59.75	0.62	....	10.18	0.64	6.55
4	9.80	15.92	25.86	23.20	3.02	....	13.16	1.42	7.62
5	10.00	7.00	14.35	50.30	....	8.40	7.30	0.84	1.81
6	7.42	4.26	16.08	51.44	....	1.53	11.25	1.19	6.83
7	12.22	5.38	17.70	37.02	....	0.79	16.76	1.63	8.50
9	12.46	11.24	36.85	21.37	....	3.13	0.72	1.02	13.21
11	17.82	10.32	5.06	37.50	6.70	....	13.92	2.25	6.43
				SERIES OF 1904					
1	26.04	10.80	1.36	27.50	3.84	.....	23.07		7.39
2	17.21	8.02	18.50	11.52	....	15.61	21.74		7.40
3	15.10	3.95	21.93	10.48	....	11.06	25.28		12.20
4	8.99	1.90	22.81	49.11	....	14.11	0.50		2.58
5	9.11	2.20	47.96	16.85	....	2.46	11.76		9.66
6	12.10	2.60	54.99	10.78	....	4.63	9.57		5.33
7a	12.93	1.35	21.83	31.14	....	5.14	15.94		11.67
7b	12.93	1.35	21.83	31.14	....	5.14	15.94		11.67
8a	12.70	2.33	35.05	17.03	....	3.99	17.85		11.05
8b	12.70	2.33	35.05	17.03	....	3.99	17.85		11.05
9	23.52	7.20	6.56	37.56	3.48	.....	5.59		16.09
10	10.05	6.47	11.71	50.98	....	7.33	4.94		8.52
11	9.75	2.08	6.05	54.71	....	5.72	6.43		15.26
12	7.98	4.68	8.89	55.61	....	11.36	3.75		7.73
				SERIES OF 1905					
3	7.09	5.05	17.16	19.45	.....	0.77	34.10	0.58	15.80
4	6.92	3.57	21.57	3.61	25.61	....	1.85	0.56	36.31
8	6.61	1.34	0.62	74.26	.....	0.15	10.87	0.68	5.47
9	8.44	2.52	12.59	56.80	.....	0.33	11.43	0.87	7.02
10	3.33	1.43	5.82	67.99	1.64	....	11.11	0.48	8.20
11	7.09	2.30	14.87	58.18	.....	2.22	8.26	0.75	6.33
12	27.72	9.53	12.11	10.05	0.24	....	29.90	1.07	9.38
13	9.54	10.38	8.41	9.67	3.87	....	39.09	0.71	18.33
14	16.87	4.73	2.22	40.30	6.06	....	19.25	0.83	9.74
15	24.03	12.69	1.46	31.37	0.35	....	20.91	1.45	7.74

Table No. 7 gives a summary of the data and results. In it are given for each tube the corresponding average loss as determined by the several experiments, as well as the thickness and some of the results of analyses. From this table there have been plotted five diagrams—Fig. 6, 7, 8, 9 and 10, which exhibit the loss due to the scale with reference to thickness, hardness and chemical composition. Fig. 6 shows the loss due to scale plotted with reference to its thickness. Fig. 7 is identical with Fig. 6, except that the letters H, S or M have been added at the various points to indicate the scale as being either hard, soft, or medium. In Fig. 8, 9 and 10 the loss due to the scale is plotted with reference to the amount of its chemical constituents; in Fig. 8 with reference to the sum of the percentages of calcium carbonate and magnesium carbonate; in Fig. 9 with reference to the percentage of calcium sulphate; and in Fig. 10 with reference to the percentage of silica.

In the series of 1901 there are a few tests which indicate an increase of conductivity of the scaled tube as compared with the clean tube. These are perhaps to be accounted for by errors in conducting the experiments, although they could not be detected at the time the experiments were made. The apparatus used in 1904 and 1905 was improved in some particulars, the most important change being in the means for the measurement of furnace temperatures. Such discrepancies disappear in the latter series.

When the experiments were planned it was considered probable that the transmission of heat through the scale was principally dependent upon two of its characteristics, namely, its thickness and its mechanical structure and that probably, for such thicknesses as are usually met with, thickness had greater influence than structure. Thickness was therefore carefully determined and structure approximately designated as in Table 4, as hard, soft or medium, no more exact characterization of structure being possible with tubes collected from different sources as these were.

It was hoped that the experiments might develop, if perhaps only approximately, some law of variation of conductivity with thickness. After making allowance for probable errors due to the method of conducting the tests, consideration of Fig. 6 shows perhaps a decrease of conductivity with thickness; but certainly no regularity of variation. In Fig. 7 the loss in heat transmission is again plotted with reference to thickness; and the structure of the scale, in so far as it was determined, is indicated as previously explained. No regularity of variation is observable with respect to hardness or softness.

TABLE 7
SUMMARY

THE TRANSMISSION OF HEAT THROUGH SCALE-COVERED BOILER TUBES

RAILWAY ENGINEERING DEPARTMENT—UNIVERSITY OF ILLINOIS

SERIES OF 1901

Tube No.	Test No.	Loss per cent	Ave. Loss per cent	Character of Scale	Thickness of Scale	$CaCO_3+MgCO_3$ in Scale	Ca SO_4 in Scale	Si O_2 in Scale
1	11	*0.6	1.2	H	0.06	48.46	16.78	7.00
1	12	2.9						
2	16	13.0	10.8	S	0.06	22.27	27.30	5.68
2	18	8.5						
3	1	9.7	9.4	H	0.02	59.75	2.04	9.24
3	2	9.1						
4	20	*1.4	*3.5	H	0.03	23.20	25.86	9.80
4	21	*5.5						
5	6	6.5	7.1	H	0.13	58.70	14.35	10.00
5	22	7.6						
6	3	*2.1	0.3	✓	0.07	52.97	16.08	7.42
6	23	2.6						
7	8	6.4	3.3	M	0.04	37.81	17.70	12.22
7	9	0 2						
9	4	11.4	15.9	H	0.11	24.50	36.85	12.46
9	15	20.4						
11	7	9.1	10.5	S	0.09	37.50	5.06	17.82
11	24	11.9						

*Increase

SERIES OF 1904

Tube No.	Test No.	Loss per cent	Ave. Loss per cent	Character of Scale	Thickness of Scale	$CaCO_3+MgCO_3$ in Scale	Ca SO_4 in Scale	Si O_2 in Scale
1	15	5.1	....	H	0.04	27.50	1.36	26.04
2	16	9.8	....	S	0.07	27.13	18.50	17.21
3	17	8.6	....	S	0.08	21.54	21.93	15.10
4	18	2.0	....	S	0.05	63.22	22.81	8.99
5	19	6.5	....	S	0.04	19.31	47.96	9.11
6	20	7.2	....	S	0.08	15.41	54.99	12.10
7a	13	11.0	....	S	0.06	36.28	21.83	12 93
7b	14	12.4	....	S	0.06	36.28	21.83	12.93
8a	12	11.1	....	H	0.05	21.02	35.05	12.70
8b	11	9.3	....	H	0.04	21.02	35.05	12.70
9	10	12.6	....	H	0.06	37.56	6 56	23.52
10	7	8.5	....	H	0.03	58.31	11.71	10.05
11	8	15.0	....	S	0 09	60.43	6.05	9.75
12	9	7.2	....	S	0.03	66.97	8.89	7.98

SERIES OF 1905

Tube No.	Test No.	Loss per cent	Ave. Loss per cent	Character of Scale	Thickness of Scale	$CaCO_3+MgCO_3$ in Scale	Ca SO_4 in Scale	Si O_2 in Scale
3	48	2.8						
3	49	1.9	2 5	M	0.07	20.22	17.16	7.09
3	50	2.7						
4	45	3.0						
4	46	4.8	4.5	H	0.05	3.61	21.57	6.92
4	47	5.6						
8	24	4.5						
8	25	3.6	4.8	S	0.03	74.41	0.62	6.61
8	26	6.3						
9	27	3.3						
9	28	5 2	3.8	S	0.09	57.13	12.59	8.44
9	29	2 8						
10	30	2.9						
10	31	3.1	3.3	S	0.07	67.99	5.82	3.33
10	32	3.8						
11	34	6.2	8.0	S	0.04	60 40	14.87	7.09
11	35	9.8						
12	37	4.7	5.7	H	0.07	10.05	12.11	27.72
12	38	6.6						
13	39	2.3						
13	40	1.3	1.6	H	0.02	9.67	8,41	9.54
13	41	1.2						
14	43	4.4	4.4	M	0.04	40.30	2.22	16,87
14	44	4.3						
15	51	3.8	3.6	H	0.03	31.37	1.46	24 30
15	52	3.4						

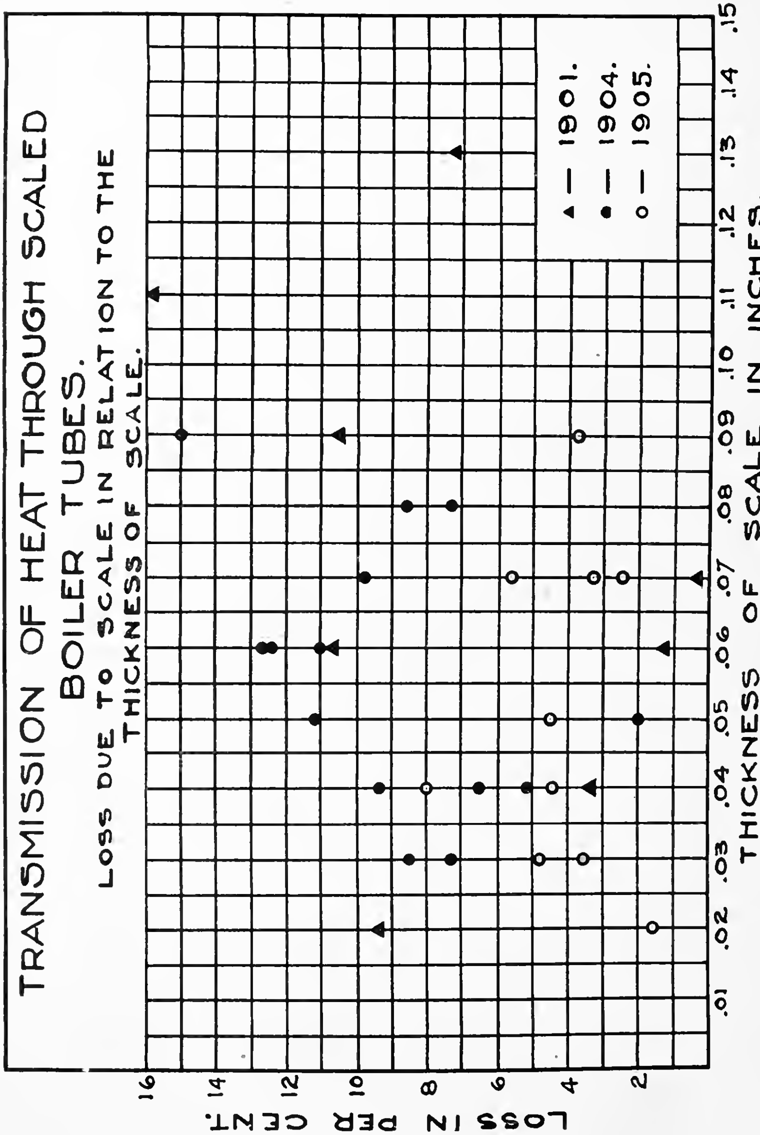

TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE THICKNESS OF SCALE.
▲— 1901.
●— 1904.
○— 1905.
.01 .02 .03 .04 .05 .06 .07 .08 .09 .10 .11 .12 .13 .14 .15
THICKNESS OF SCALE IN INCHES.
16 14 12 10 8 6 4 2
LOSS IN PER CENT.

FIG. 6

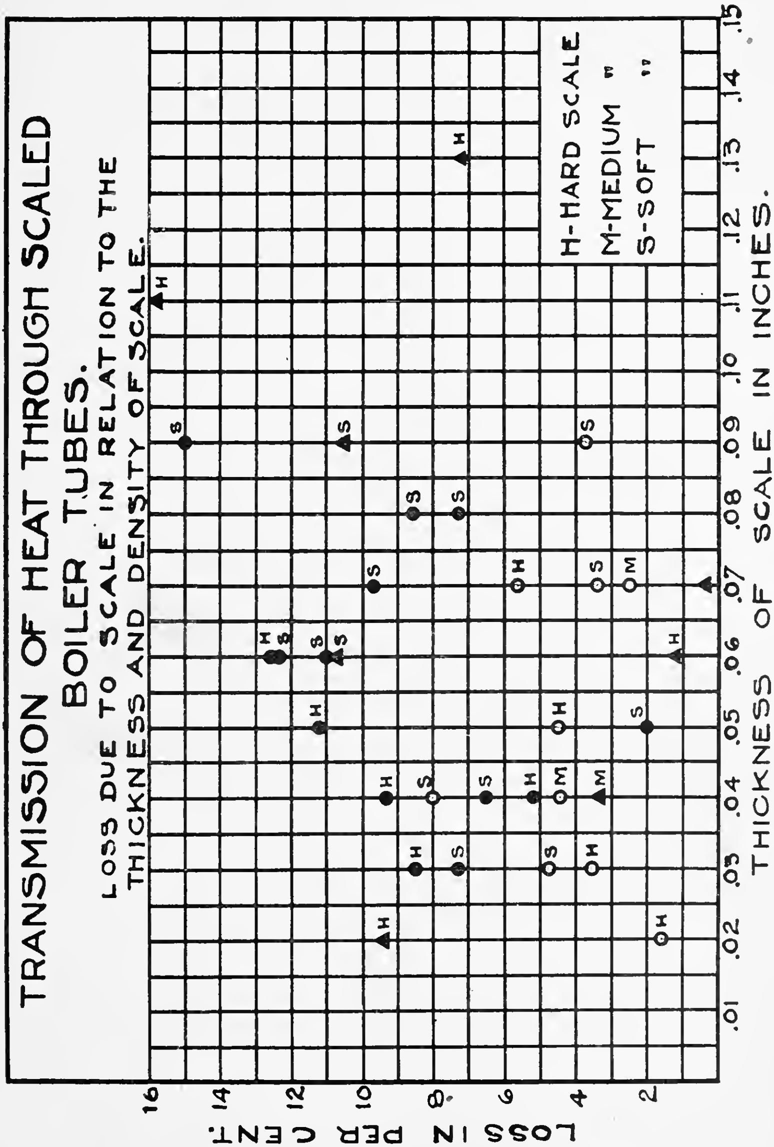

TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE THICKNESS AND DENSITY OF SCALE.
H-HARD SCALE
M-MEDIUM "
S-SOFT "
LOSS IN PER CENT.
16
14
12
10
8
6
4
2
THICKNESS OF SCALE IN INCHES.
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.11
.12
.13
.14
.15

Fig. 7

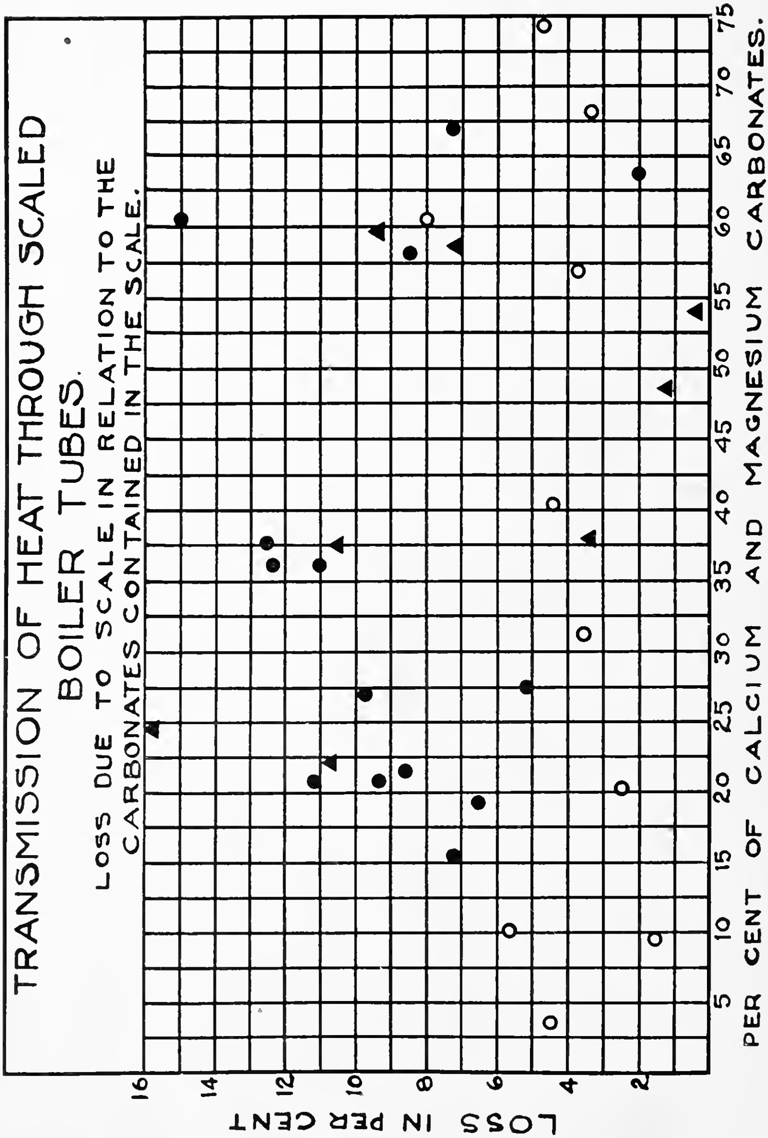

TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE CARBONATES CONTAINED IN THE SCALE.
LOSS IN PER CENT
16
14
12
10
8
6
4
2
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
PER CENT OF CALCIUM AND MAGNESIUM CARBONATES.

FIG. 8

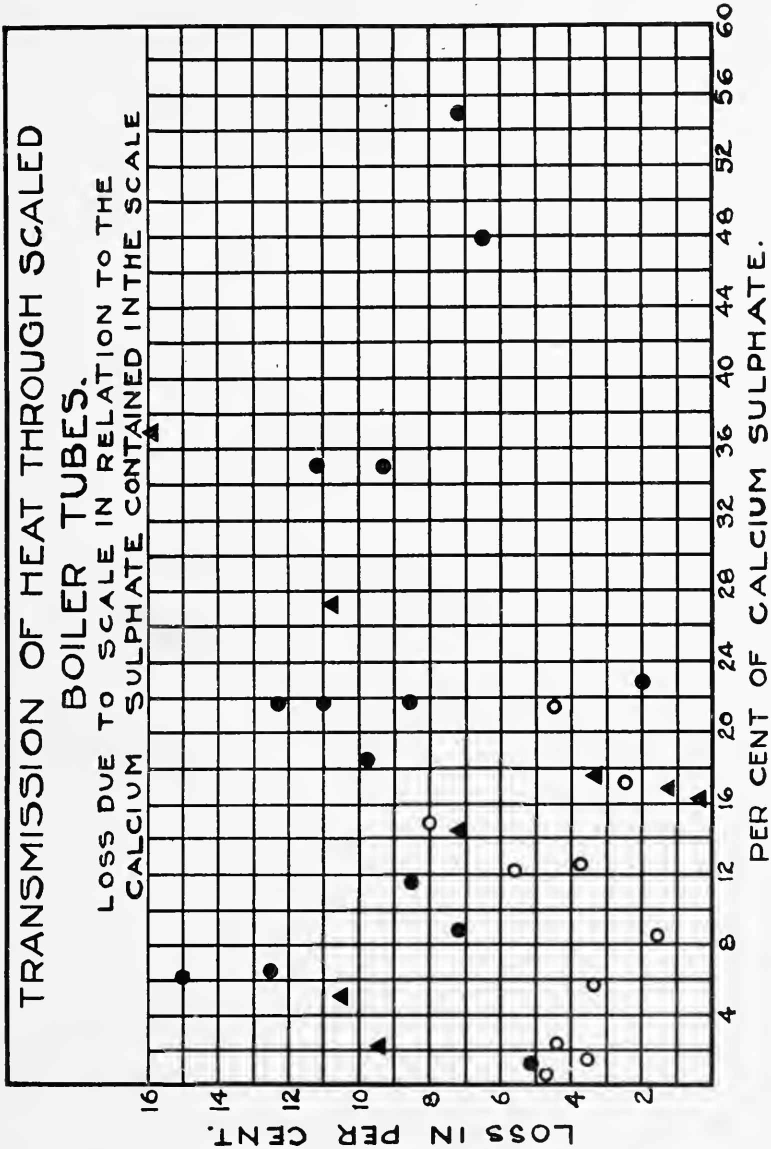

TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE CALCIUM SULPHATE CONTAINED IN THE SCALE
LOSS IN PER CENT.
16 14 12 10 8 6 4 2
4 8 12 16 20 24 28 32 36 40 44 48 52 56 60
PER CENT OF CALCIUM SULPHATE.

FIG. 9

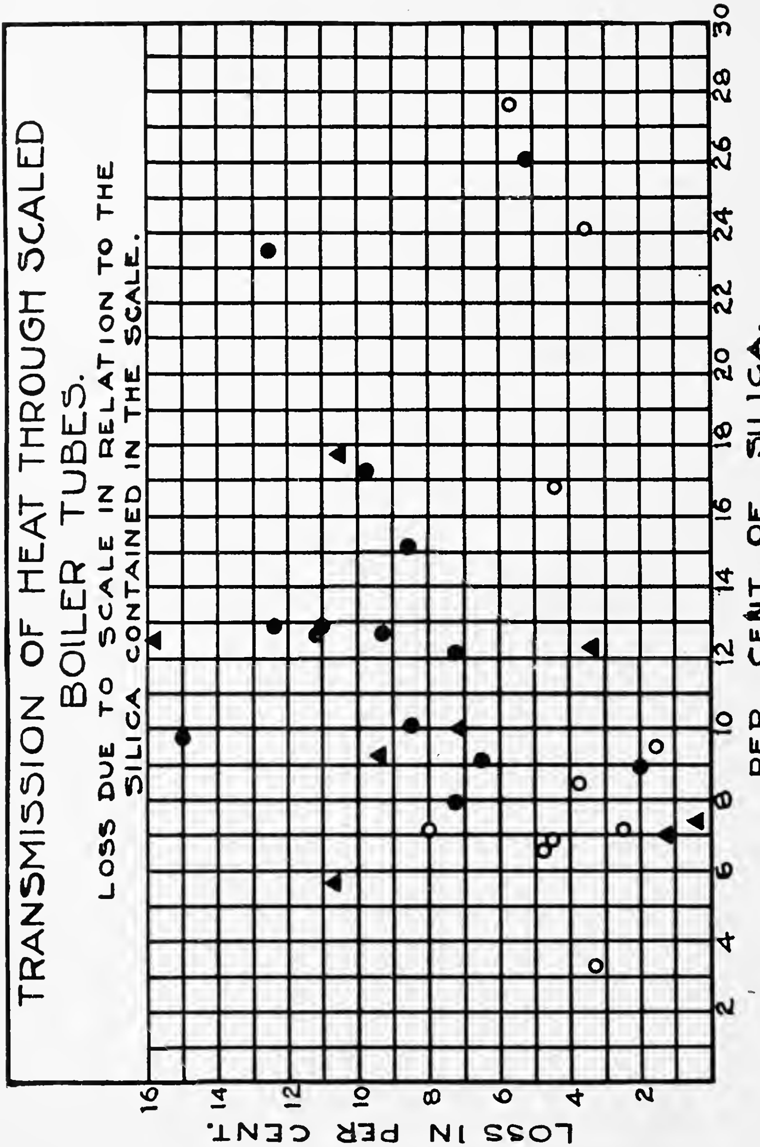

TRANSMISSION OF HEAT THROUGH SCALED BOILER TUBES.
LOSS DUE TO SCALE IN RELATION TO THE SILICA CONTAINED IN THE SCALE.
LOSS IN PER CENT.
16
14
12
10
8
6
4
2
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
PER CENT OF SILICA.

Fig. 10

In considering Fig. 6 and 7 it must be borne in mind that the tubes tested were taken from locomotives which had been in service in different parts of the country and that the scale on each tube was made up of the mineral constituents of many different water supplies. What is designated as hard scale in one case may be very different in structure—in porosity, for example—from what is designated as hard scale on another tube. Fig. 7 cannot therefore be considered as providing conclusive evidence concerning variation of conductivity with structure. The results may properly be interpreted as indicating that mechanical structure is at least as important a factor in the change in heat transmission due to scale as is the mere thickness. Such a conclusion is, of course, in accord with the facts concerning other heat insulators.

Fig. 8, 9 and 10, in which the loss in heat transmission is plotted with reference to the principal chemical constituents of the scale, do not warrant the conclusion that its chemical composition has any direct influence on its conductivity.

From the point of view of the physicist the experiments are open to objection as to method. From the engineer's viewpoint it is believed that the possible errors of the experiments do not, by any means, account for all the irregularity in the plotted results, and considering the controversy upon this subject and the comparatively meager information available, it is deemed proper to publish at this time the results as they stand in the hope that they contribute additional information which may be of interest in some quarters.

Conclusions:

In so far as generalization is warranted we may sum up the results of the tests in the following conclusions:

1. Considering scale of ordinary thickness, say of thicknesses varying up to $\frac{1}{8}$ inch, the loss in heat transmission due to scale may vary in individual cases from insignificant amounts to as much as 10 or 12 per cent.

2. The loss increases somewhat with the thickness of the scale.

3. The mechanical structure of the scale is of as much or more importance than the thickness in producing this loss.

4. Chemical composition, except in so far as it affects the structure of the scale, has no direct influence on its heat transmitting qualities.

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Bulletin No. 12. Tests of Reinforced Concrete T-Beams, Series of 1906, by Arthur N. Talbot. 1907.

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UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 12. FEBRUARY 1907

TESTS OF REINFORCED CONCRETE T-BEAMS SERIES OF 1906.

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY ENGINEERING AND IN CHARGE OF THEORETICAL AND APPLIED MECHANICS.

CONTENTS.

IV. EXPERIMENTAL DATA AND DISCUSSION.

I. Introduction.

1. *Preliminary.*—The series of tests on T-beams herein described was undertaken with two objects in view,—to determine whether the width of slab within the limit used in the experiments is a controlling element in the strength of the beam, and to test the efficacy of vertical reinforcing stirrups in resisting web stresses.

When a reinforced concrete floor and its supporting beams are built as one piece, the resulting composite structure forms a system of T-shaped beams. There are differences of opinion on the action of the T-beams so formed, and also differences as to the width of flange or floor which may be considered to contribute to the strength and stiffness of the beam. T-shapes may also be used in the design of bridge girders and other structures for special conditions. The large amount of reinforcement which may be put into a T-beam without encroaching on the compressive strength of the concrete too far and the resulting high web stresses developed in the stem of the T-beam, make the T-beam an advantageous form of test piece for determining the efficacy of various forms and amounts of web reinforcement. It is felt that this feature of T-beam testing is, in itself, sufficient reason for the conduct of tests on T-beams.

2. *Scope of Tests.*—Three top widths of beam were used, equal, respectively, to two, three, and four times the width of the stem of the beam. The beams were reinforced vertically with U-shaped stirrups. One size and spacing of stirrups was used. To insure that failure would not occur by slipping of the vertical reinforcement in the concrete, the stirrups were made of deformed bars. The amount of longitudinal reinforcement was made proportional to the width of flange of the beam. Both mild steel plain round rods and high-carbon Johnson corrugated bars were used for the longitudinal reinforcement, as it was not known whether the point of elastic limit of the metal would control the amount of load or method of failure. As no data on the amount of the web stresses which may be resisted by vertical stirrups were available and as little seemed to be known on the effect of the width of flange or slab, the beams were designed to give considerable latitude in the results The series was considered as preliminary and leading to a set of

tests which should include various forms and amounts of web reinforcement.

3. *Acknowledgment.*—The investigation was made in the Laboratory of Applied Mechanics of the University of Illinois as a part of the work of the University of Illinois Engineering Experiment Station. Assistance in the tests and in the calculations was given by F. S. Hewes and C. A. Hewes, senior students in civil engineering, class of 1906, who used the results in their thesis. Immediate supervision of the work of making the beams and conducting the tests was given by D. A. Abrams, Assistant in the Engineering Experiment Station. Acknowledgment is also made to W. R. Robinson, Assistant in the Engineering Experiment Station, for aid in the preparation of this bulletin. The stone, sand and cement used in making the beams were furnished by the Joint Committee on Concrete and Reinforced Concrete.

An analysis of some of the elements of flexure of T-beams will be given. This will be followed with a description of the test pieces and method of testing, the experimental data, and a discussion of the results.

II. Resistance of T-beams to Flexure

4. *General.*—The analysis of the resistance of T-beams to flexure may be made to follow the general lines of analysis for rectangular beams. If the tensile strength of the concrete be not considered at sections having a maximum bending moment and if the flange or slab extends down to the neutral axis of the beam, the resisting moment may be expected to be the same as that for a rectangular beam of width equal to the width of the flange, provided, of course, that the integrity of the plane section is conserved. If the flange does not extend down to the neutral axis, an examination of the effect of the omission of a part of the compression area must be made to find whether the formula for rectangular beams is still applicable. With relatively shallow flanges some modification of the formulas used in rectangular beams for determining neutral axis, tensile and compressive stresses, and resisting moment may be required. In the determination of web stresses, a slightly different treatment will be needed on account of the narrowed width of beam through the stem. The stiffness and integrity of the flange next to its junction with the stem will require investigation.

In the treatment here given, the usual assumptions of beam action noted in Bulletin No. 4 will be made. These include the assumptions that a plane section before bending will remain a plane section after bending and that tensile stresses in the concrete at the section of greatest bending moment may be neglected. The stresses developed in the flange to conserve the plane section will be considered separately. The general treatment will follow that given in Bulletin No. 4 of the University of Illinois Engineering Experiment Station, under I. RESISTANCE OF BEAMS TO FLEXURE, and equations from this source will be quoted without demonstration. The term "inclosing rectangle" will be used to denote the rectangle inclosing the flange of the T-beam and the stem down to the centroid of the reinforcing bars.

5. *Notation.*—The following notation will be used, Fig. 1:

h = thickness of flange or slab of T-beam.

b = breadth of flange or slab of T-beam.

b' = breadth of stem of T-beam.

d = distance from the compressive face to the centroid of the longitudinal reinforcement.

d' = distance from the center of the longitudinal reinforcement to center of gravity of compressive stresses.

A = area of cross section of longitudinal reinforcement.

bd = area of inclosing rectangle (rectangle inclosing flange and stem of T-beam down to center of the longitudinal reinforcement).

$p = \frac{A}{bd}$ = ratio of area of longitudinal reinforcement to area of inclosing rectangle.

o = circumference or periphery of one reinforcing bar.

m = number of reinforcing bars.

E_s = modulus of elasticity of steel.

E_c = initial modulus of elasticity of concrete in compression, a term defined in Bulletin No. 4.

$n = \frac{E_s}{E_c}$ = ratio of two moduli.

f = tensile stress per unit of area in longitudinal reinforcement.

c = compressive stress per unit of area in most remote fiber of concrete.

c' = compressive stress per unit of area which causes failure by crushing.

ε_s = deformation per unit of length in the longitudinal reinforcement.

ε_c = deformation per unit of length in most remote fiber of the concrete.

ε'_c = deformation per unit of length when crushing failure occurs; i. e., ultimate or crushing deformation.

$q = \frac{\varepsilon_c}{\varepsilon'_c}$ = ratio of deformation existing in most remote fiber to ultimate or crushing deformation.

k = ratio of distance between compression face and neutral axis to distance d.

z = distance from compression face to center of gravity of compressive stresses.

M = resisting moment at the given section.

s = horizontal tensile stress per unit of area in the concrete.

t = diagonal tensile stress per unit of area in the concrete.

u = bond stress per unit of area on the surface of the reinforcing bar.

v = vertical shearing stress and horizontal shearing stress per unit of area in the concrete.

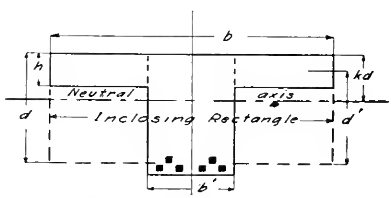


FIG. 1. T-BEAM AND INCLOSING RECTANGLE.

6. *Longitudinal, Tensile and Compressive Stresses, and Location of Neutral Axis.—Approximate Solution.*—Under the assumption that horizontal tensile stresses in the concrete are not to be considered and that a plane section before bending remains a plane section after bending, the formulas for rectangular beams may be made applicable to T-beams with a close degree of approximation by the substitution of the rectangle inclosing the flange and stem down to the centroid of the reinforcing bars (called here the inclosing rectangle) shown in Fig. 1. If the flange of the T-beam were thick enough to extend down to or below the neutral axis, the part of the concrete not included in the inclosing rectangle would, by the assumptions quoted above, not affect the resistance of the beam

to flexure. If the flange does not extend to the neutral axis, a part of the compression area assumed to exist for the inclosing rectangle is not available in the T-beam, but the portion so cut off has, by reason of its proximity to the neutral axis, a comparatively small influence upon the flexural action of the beam. The effect is so little that we may, within certain limits of proportions, substitute the inclosing rectangle for the T-section in determining the position of the neutral axis, the tensile stress in the reinforcement, the compressive stress in the most remote fiber of the concrete, and the resisting moment of the section.

For this approximation, the formulas given in Bulletin No. 4 for the proportional depth of the neutral axis may be repeated:

For a constant modulus of elasticity in the concrete (straight-line stress-deformation relation),

$$k = \sqrt{2\,pn + p^2n^2} - pn \qquad (10)$$

When the deformation in the most remote fiber is equal to one fourth of the ultimate or crushing deformation ($q = \frac{1}{4}$), a condition approaching that found in beams of the usual percentage of reinforcement, the general equation for neutral axis reduces to,

$$k = \sqrt{\tfrac{24}{11}\,pn + \tfrac{144}{121}\,p^2n^2} - \tfrac{12}{11}pn \qquad (11)$$

Equation (8) of Bulletin No. 4 may be used for the general case and (9) when the concrete is at the limit of the compressive strength.

The diagram given on page 16 of Bulletin No. 4 will be useful in determining the position of the neutral axis if equation (11) is to be used. With 1% reinforcement, for a ratio n equal to 12, k will be .40; for a ratio n equal to 15, k will be .43.

For a beam in which the compressive stress developed is less than the ultimate strength of the concrete (and this condition covers all the usual cases of T-beams), the formula for the resisting moment of the beam may best be expressed in terms of the tensile stress in the reinforcing bars, as given in the two equations:

$$M = Af\,(d - z) \qquad (12)$$

$$M = A\,f\,d' \qquad (13)$$

If $k = .40$, or $.43$, the latter equation may be written $M = .86 A f d$, and this equation for the resisting moment of the T-beam may be used with sufficient accuracy for many purposes, even for quite a range of reinforcement. If the bending moment is known, the stress in the steel may be calculated by substituting the value of the bending moment for M in equation (13) or in the reduced form $M = .86 A f d$. The effect of substituting the inclosing rectangle for the exact T-shape in determining the position of the neutral axis and the center of the compressive stresses is so slight that the error may be neglected and the above formulas used when the flange extends at least two thirds of the distance to the neutral axis or, say, when the thickness of the flange is at least one fourth of the depth of the beam. Even for thinner flanges the error in the use of these formulas will not be large.

Values for compressive stresses in T-beams are not of very general usefulness since the percentage of reinforcement (based on the inclosing rectangle) will generally not be large and the compressive stresses may therefore not need to be considered and may be sufficiently guarded by limiting the percentage of reinforcement. To illustrate, if in a T-beam made up of a beam and its connecting portion of the floor a width equal to four times the width of the beam itself be considered to be tributary to the T-beam and if the area of the reinforcing bars is 4% of the area inclosing the stem of the T-beam ($b'd$, of Fig. 1), this reinforcement will be only 1% of the inclosing rectangle of the assumed T-beam. Under conditions of good construction, the compressive stress developed in the concrete, would, as has been shown for rectangular beams, be well below any danger of a compression failure. This amount of steel is larger than would ordinarily be used in such construction.

If, however, it is desired to compute the compressive stress, an approximate solution may be made by equation (15) of Bulletin No 4,

$$c = \frac{2Af}{kbd}\cdot\frac{1-\frac{1}{2}q}{1-\frac{1}{3}q} = \frac{2pf}{k}\cdot\frac{1-\frac{1}{2}q}{1-\frac{1}{3}q}\qquad(15)$$

where b and p refer to the inclosing rectangle. For the conditions of T-beams the fraction $\frac{1-\frac{1}{2}q}{1-\frac{1}{3}q}$ will likely range between

.92 and .97, so that its use or non-use does not affect the results materially.

There is a greater proportional error in the use of equation (15) for beams in which the flange does not extend down to the neutral axis than there is in the use of equation (13), but as the purpose is only to find whether a limiting value is exceeded, the limits for depth of flange used with equation (13) may be considered allowable. This is further borne out by the fact that in floor systems a width of floor even greater than here used will generally be tributary to the T-beam, and hence the compressive stress will be lower than for an assumed ratio of 4.

7. *Web Stresses.—Bond, Shear, and Diagonal Tension.*—In T-beams the bond stresses developed are practically the same as would be found with the same steel in a rectangular beam. The shearing stresses developed and the corresponding diagonal tensile stresses are higher, since the width of stem is relatively small; and even with a moderate amount of reinforcement the resistance to web stresses may constitute the weakest element of the beam.

The bond stress developed in a T-beam when the longitudinal reinforcing rods are laid horizontally throughout the length of the beam may be determined by equation (17) of Bulletin No. 4, (p. 19),

$$u = \frac{V}{mod'} \qquad (17)$$

where u is the bond unit-stress developed, V is the total external vertical shear, m is the number of reinforcing bars, o is the effective circumference or periphery of one bar, and d' is the distance from the center of the longitudinal reinforcement to the center of gravity of the compressive stresses. The only approximation to be made is in getting the value of d'. As in the preceding article, d' may be taken to be $d\ (1 - .34\ k)$, and k may be obtained as before suggested by the use of the method of rectangular beams with the width of the beam taken as that of the inclosing rectangle. For most conditions d' may be called $.86d$.

The reasoning for the determination of vertical and horizontal shearing stresses given on page 20 of Bulletin No. 4 is directly applicable to T-beams, and formula (18) will give the horizontal shearing unit-stress (and therefore its equal, the vertical shear-

ing unit-stress), if we use in it the width b', the width of the stem of the T-beam.

$$v = \frac{V}{b'd'} \quad \text{...(18)}$$

In equation (18) v is either the horizontal or the vertical shearing unit-stress, the two shearing unit-stresses being always equal. For most conditions d' may be taken as $.86d$, as in the last paragraph. The amount of the vertical shearing unit-stress developed in T-beams may be much higher than in ordinary rectangular beams, but it will be well below the ultimate shearing strength of the concrete.

The diagonal tensile stress in the stem of the T-beam is a function of the shearing stress and the horizontal tensile stress in the concrete. As the horizontal tensile stresses may not be well determined, it seems best for our purpose to use the horizontal and vertical shearing stresses as a means of comparison of the diagonal tensile stress developed. If part or all of the reinforcing bars are bent up at the ends, the problem is further complicated. The beams described in this bulletin were reinforced with vertical stirrups, and as the concrete itself failed to resist the diagonal tension at points well below the maximum load put on the beam, the resistance of the concrete to diagonal tension will be disregarded for these tests and the effect of the vertical stirrups studied.

Two forms of metallic web reinforcement are used to counteract the diagonal tension: (1) bending the reinforcing bars or strips sheared from them into a diagonal position, and (2) vertical stirrups carried under and around the longitudinal reinforcement and extended upward to the top of the beam or to some anchorage. The T-beams tested were reinforced with vertical stirrups, and hence this form of web reinforcement will be considered further.

The diagonal tension existing in the web may be resolved into horizontal and vertical components. Considering the longitudinal bars to be all horizontal, we may expect, when the bond resistance is sufficient, that the horizontal component will be taken by the longitudinal reinforcement. Considering that the test has passed the point where the concrete of the web resists the diagonal tension, we may count that the whole vertical component of the

web stresses is taken by the stirrups. The amount of this vertical component per unit of length of beam is for the T-beams equal to the horizontal shear for the width of the stem as given by equation (18), and $vb' = \frac{V}{d'}$ will give the rate of vertical stress per unit of length of beam which will go to the stirrups. If the stirrups are 6 inches apart, the stress to be taken by the two prongs of the stirrup will be 6 vb'. This calculation is on the basis of a test loading which gives a constant shear from support to load point, as, for example, a loading at the one-third points. For a uniformly distributed load, the value vb' will be the rate of stress at a given section. To illustrate further, for a T-beam having a width of stem of 8 in., and $d' = 8.6$ in., and a load of 60 000 lb., $V = 30\,000$ lb., and $v = 437$ lb. per sq. in. With stirrups 6 inches apart the total stress on one prong of the stirrup will be 10 500 lb. These calculations do not take into account the resistance to bending of the reinforcing bars themselves. In the T-beams having also a part of the bars bent up, in order to avoid complicated calculations and to give a general comparison, the same formulas will be used herein, although the results are not an accurate measure of the stresses produced.

8. *Integrity of Flanges.*—In discussions on T-beams it is frequently stated that the thickness of the flange must be at least one half as great as the width of the stem or rib, in order that the shearing stresses at the junction of the flange and stem may not exceed those in the lower part of the stem. As the actual shearing stresses in both sections are well within the shearing strength of the concrete, there is no danger of failure by shear in either section, using the term shear in its strict sense. In the stem we have used the shearing unit-stress as a measure or method of comparison for the diagonal tensile stresses. In the flange these stresses do not need consideration. Longitudinal shearing stresses in the flange, then, will not require consideration, and the limit of depth given above is unnecessary.

Another statement sometimes made is that the compressive stress in the flange varies across the width of the flange from a maximum amount next to the stem to zero at the edge of the flange. A little consideration will show that this cannot be true. The flange must transmit stress laterally to its edges, acting in a

way as a beam with a load applied longitudinally and horizontally. The width of the overhang of the flange may be considered to be the span of this cantilever beam, and the distance from the load to the support (one-third the span length in the beams tested) may be thought of as the depth. Evidently this will be a very stiff beam, and the result will be a close approach to uniformity of compressive stress at points across the width of the flange. Little variation from a plane section may therefore be expected, the change that may exist being produced more largely by other causes. Of course, there must be a limit to this assumed integrity of the cross section, but for T-beams with the ordinary amount of reinforcement the compressive stress developed is small and the variation may generally be neglected.

As usually constructed, the floor, and hence the flange of the T-beam, will have reinforcement at right angles to the stem. This will resist a breaking of the flange next to the stem and assist in giving the whole flange the curved shape which the beam takes when the load is applied.

9. *Method of Treatment.*—For the investigation herein recorded, the preceding method of analysis will be used. The T-beam will be treated as a rectangular beam of the dimensions given by the inclosing rectangle, when tensile, compressive, and bond stresses are under consideration. The width of the stem will be considered to enter into calculations for shear and for diagonal tension. The integrity of the cross section will be investigated somewhat, and the bearing of the approximation involved in the above assumptions will be looked into.

10. *Other Formulas for T-beams.*—If it is desired to take into account the exact section above the neutral axis the following formula for the proportionate depth of the neutral axis may be used, if we consider $q = 0$, or if we use a straight-line modulus of elasticity. Other values of q may be used.

$$k = \sqrt{2\,pn\left(\frac{b}{b'}\right) - \frac{h^2}{d^2}\left(1 - \frac{b}{b'}\right) + \left[pn\left(\frac{b}{b'}\right) + \frac{h}{d}\left(\frac{b}{b'} - 1\right)\right]^2}$$
$$- pn\left(\frac{b}{b'}\right) - \frac{h}{d}\left(\frac{b}{b'} - 1\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (10')$$

For a beam with 1% reinforcement and having a ratio of depth of flange to effective depth of steel $\left(\frac{h}{d}\right)$ of $\frac{1}{4}$, using for

comparison $n = 15$, this formula gives $k = .44$, and the approximate method previously described gives $k = .42$. For $\frac{h}{d} = \frac{1}{5}$, $k = .46$. It is easily seen that the effect of this difference upon the calculated resisting moment of the beam (when based on tension in the steel) is small.

III. Materials, Test Pieces, and Method of Testing.

11. *Materials.*—The stone was a good quality of rather hard limestone from Kankakee, Illinois, ordered screened through a 1-in. screen and over a $\frac{1}{4}$-in. screen. It contained 45% to 50% voids and weighed 85 pounds per cubic foot. In the determination of the voids of both stone and sand, the material was poured slowly into water so that the voids became filled with water and no air was caught.

The sand was of good quality from near the Wabash river at Attica, Indiana. It was fairly clean, sharp and well graded, contained 28% voids, and weighed 115 lb. per cu. ft. Table 1 gives the results of a mechanical analysis of this sand.

TABLE 1.

Mechanical Analysis of Sand.

Sieve No.	Per cent Passing
4	100
10	73
20	36
30	12
74	5
100	2

The cement used was furnished by the Joint Committee on Concrete and Reinforced Concrete. It was made up of a mixture of five standard American portland cements, selected and mixed by the manufacturers and was of excellent quality.

The concrete was made of the proportions of 1 of cement, 2 of sand, and 4 of stone, measured by loose volume. The mixing was done and the beams made by men skilled in concrete work. Care was taken in measuring, mixing, and tamping, to secure as uniform a concrete as possible. The mixing was done with

shovels by hand; the stone having been wetted a day or so before being used. The sand and cement were first mixed dry, the stone being then added and the mass mixed until uniform in appearance. Water was added in such proportion that the tamping of the central portion of the beam really amounted to a churning action.

The steel used for the horizontal reinforcement in some of the beams was $\frac{3}{4}$-in. mild steel plain round rods, and in the rest was $\frac{3}{4}$-in. high steel Johnson corrugated bars. The stirrups were in all cases $\frac{1}{2}$-in. high steel Johnson corrugated bars. Table 2 gives physical tests of these rods, the samples tested being from

TABLE 2.

TENSION TESTS OF STEEL USED IN T-BEAMS.

Average Values.

T-beam No.	Size of Bar inches	Per cent Elongation in 8 in.	Yield Point pounds	Maximum Load pounds	Yield Point lb. per sq. in.	Maximum Load lb. per sq. in.
1	$\frac{3}{4}$-in. Johnson	13.5	30 700	51 300	54 900	91 600
2	bar (new section)	15.0	30 250	48 000	53 750	86 200
3	Area=.56 sq. in.	14.5	29 700	50 000	52 700	89 000
5		15.0	30 100	48 900	53 380	86 980
Av.		14.5	30 200	49 500	53 800	88 400
4	.750 plain round	34.5	16 600	24 600	35 100	55 500
8	.752 plain round	30.8	18 100	26 600	40 700	59 900
9	.750 plain round	32.0	17 300	26 100	39 100	59 100
Av.		32.4	17 300	25 800	38 300	58 200

the ends left after the bars were cut for the beam. The average ultimate strength of the plain round rods was 58 200 lb. per sq. in. and the yield point 38 300 lb. per sq. in. The $\frac{3}{4}$-in. Johnson bars developed an average ultimate strength of 88 400 lb. per sq. in., and a yield point of 53 800 lb. per sq. in.

12. *Test Specimens.*—Table 3 shows the specimens which were made and tested. The nine T-beams were 11 ft. long and the span used was 10 ft. The following dimensions were constant for all the beams: thickness of flange, $3\frac{1}{4}$ in.; width of web, 8 in.; depth over all, 12 in. and depth from top fiber to center of steel, 10 in. The width of flange varied, three speci-

mens being made of each of the widths; 16 in., 24 in., and 32 in.

The proportion of reinforcement was from .92% to 1.10%, based on the area of the inclosing rectangle, as shown in Fig. 2; that is, it was obtained by dividing the area of the steel by the product of the breadth of the flange and the effective depth of the beam. This percentage was made as near 1.00 as the size of the reinforcing bars would permit. It will be noted that if the percentage were based on the area of the rectangle inclosing the stem, it would be very high, the amount for the beams 32 in. wide amounting to about 4%. The reinforcing rods were symmetrically arranged with respect to the axis of the beam. In some, a part

TABLE 3.

LIST OF TEST SPECIMENS.

All Beams Have Stirrups of ½ in. Johnson Bars Placed as Shown in Fig. 2.

T-beams					Minor Specimens	
T-beam No.	Width of Flange inches	Reinforcement: Kind	Area: sq. in.	Area: per cent	Cubes	Cylinders
1	16	3 ¾-in. Johnson bars	1.68	1.05	1_1, 1_2, 1_3	1
2	32	6 ¾-in. Johnson bars	3.36	1.05		2
3	24	4 ¾-in. Johnson bars	2.24	0.93	3_1, 3_2, 3_3	3
4	16	4 ¾-in. plain round	1.76	1.10		4
5	32	6 ½-in. Johnson bars, 2 bars bent up	3.36	1.05	5_1, 5_2	5
6	24	5 ¾-in. plain round, 2 bars bent up	2.20	0.92		
7	16	4 ¾-in. plain round	1.76	1.10	7_1, 7_2, 7_3	7
8	24	5 ¾-in. plain round, 2 bars bent up	2.20	0.92	8_1, 8_2, 8_3	8
9	32	7 ¾-in. plain round, 3 bars bent up	3.08	0.97		

of the rods was turned up beyond the one third points to within 4 in. of the top of the beam. Ten U-shaped stirrups of ½-in. high steel Johnson corrugated bars were used in each beam. These stirrups were spaced 6 in. apart on the portions of the beam between the load points and supports. They passed under the corrugated

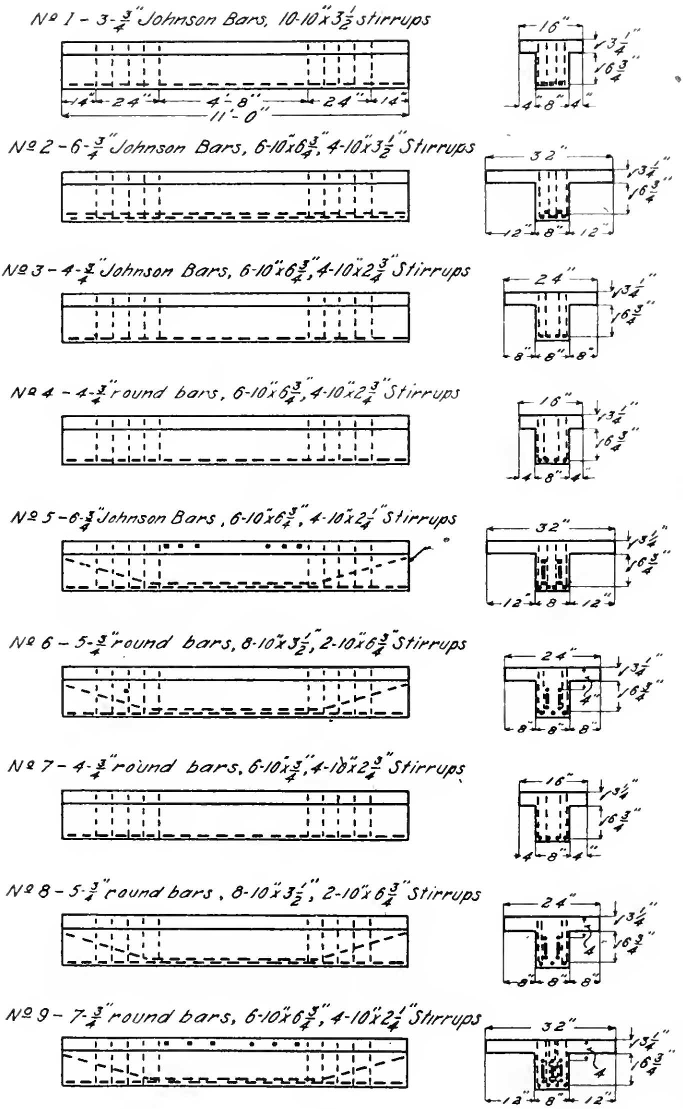


FIG. 2. ARRANGEMENT OF REINFORCEMENT.

reinforcing bars, alternate ones inclosing only the middle bars. In two of the 32-in. beams three ½-in. Johnson corrugated bars were placed transversely in the upper side of the flange at and near the load points. Fig. 2 shows the arrangement of the reinforcement in all of the beams. In some of the beams in which the reinforcing bars were placed in two layers, the upper bars sank down in the mortar until they were in contact with the lower layer of bars.

Fourteen 6-in. cubes were tested. The numbering is the same as that for the beams for which the batch was made. Seven 8-in. cylinders were made in a similar manner.

13. *Forms.*—Fig. 3 shows the plan of the forms used in making the T-beams. 2-in. planks were used for the sides and ends. Clamps and struts were of 2-in. x 4-in. pieces. The planks

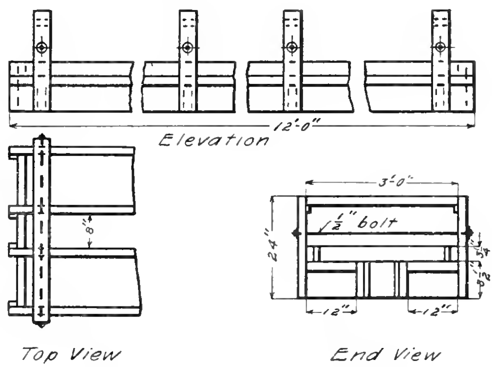


Fig. 3. Plan of Forms.

were soaked in water for some time before using, in order to prevent the absorption of water from the beams.

14. *Fabrication and Storage.*—The beams were made on the concrete floor of the laboratory, strips of building paper being laid on the floor to prevent the concrete from adhering to it. As already stated, the concrete was proportioned by loose volume and mixed by hand. Generally, two batches were mixed in making a beam.

After the form was set up, a layer of concrete 1-in. to 1½ in. thick was put in, the reinforcement placed, and the rest of the concrete filled in in layers about 3 in. thick. The sides and ends were spaded, the concrete tamped, then spaded again and tamped. This gave a very good surface to the test pieces.

The forms were kept on until a day or so before testing the beams, the beams being sprinkled twice daily in the meantime. The temperature of the room ranged from 60° to 70° F. during the period of storage.

15. *Method of Testing.*—Fig. 4 shows the method of loading used. The beams were tested in the 600 000-lb. Riehle' testing machine, the load being applied at the one-third points through turned steel rollers, which were 2 in. or $4\frac{1}{2}$ in. in diameter, according to the size of the beam. Each of these rested on a cast iron plate, 2 in. x 3 in. x 2 ft. 8 in., faced on both sides, which distributed the load laterally over the beam. The supports had curved bottoms to permit rocking, and plates 8 in. x $1\frac{1}{8}$ in. x 8 in. were used as bearing plates. These plates, together with the bearing plates on the top of the beam, were bedded in

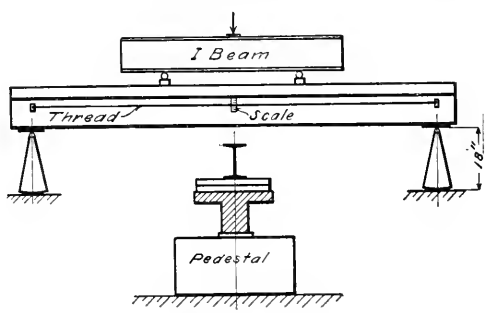


FIG. 4. METHOD OF TESTING.

plaster of paris which was allowed to harden under the weight of the beam and the aparatus used in loading, before the load was applied. The movement of the head, in testing, was $\frac{1}{20}$ inch per minute. Center deflections were read on all T-beams and deformations were observed on a few. The deflections were obtained by means of a thread stretched between two points over the supports and about seven inches from the top of the beam. The frame used for holding the extensometer dials was improvised and its lack of rigidity seriously impaired its usefulness, the readings being sometimes inconsistent and therefore untrustworthy. Since at the present time tests are being made here in which reliable deformation readings are expected, diagrams from the readings taken in this series will not be reproduced.

The cubes, cylinders, and steel were tested on the 100 000-lb.

Riehle' machine, the speed of the head being .1 inch per minute. The cubes and cylinders were bedded in plaster of paris before testing.

IV. Experimental Data and Discussion.

16. *Cube and Cylinder Test Data.*—Table 4 gives the results of the tests of the cubes and cylinders. The breaking strength of the cylinders is somewhat below that of the cubes. The concrete showed very good quality.

17. *Deflection Diagrams.*—Fig. 7 to 15 at the end of the text give the load-deflection diagrams for the T-beams. The ordinates (vertical distances) represent the applied loads, and the abscissas

TABLE 4.

Results of Cube and Cylinder Tests.

Cubes

No.	Age at Test Days	Maximum Load Total Pounds	Maximum Load lb. per sq. in.
1_1	59	62 120	1720
1_2	59	84 690	2350
1_3	59	66 390	1840
Av.			1970
3_1	57	42 120	1170
3_2	57	49 620	1380
3_3	57	46 200	1280
Av.			1280
5_1	58	69 800	1940
5_2	58	81 500	2260
Av.			2100
7_1	56	57 600	1600
7_2	56	71 100	1980
7_3	56	68 300	1900
Av.			1830
8_1	54	68 100	1890
8_2	54	55 600	1540
8_3	54	94 500	2620
Av.			2020
Average of all cubes,			1820

Cylinders

No.	Age at Test Days	Maximum Load Total pounds	Maximum Load lb. per sq. in.
1	63	95 000	1890
2	63	94 200	1870
3	61	88 200	1760
4	59	67 000	1330
5	58	60 000	1190
7	56	73 000	1450
8	54	88 000	1750
Av.			1610

(horizontal distances) the corresponding deflection at the center of the beam. It will be seen that at or near the maximum load the curve changes direction abruptly, and that for nearly all the

beams the load does not fall off materially until a considerable deflection has been obtained. The stress-deformation curves found (not reproduced) show an abrupt change on the tension side of the beam.

18. *Phenomena of Tests.*—In Table 5 (p. 25) are given the maximum loads which the beams sustained. Fig. 5 and 6 give sketches showing position of cracks as they appeared after the maximum load and also the shape of the flange in Beam No. 2 after it broke off. The general phenomena of the tests of the T-beams were quite similar to those attending the tests of rectangular beams

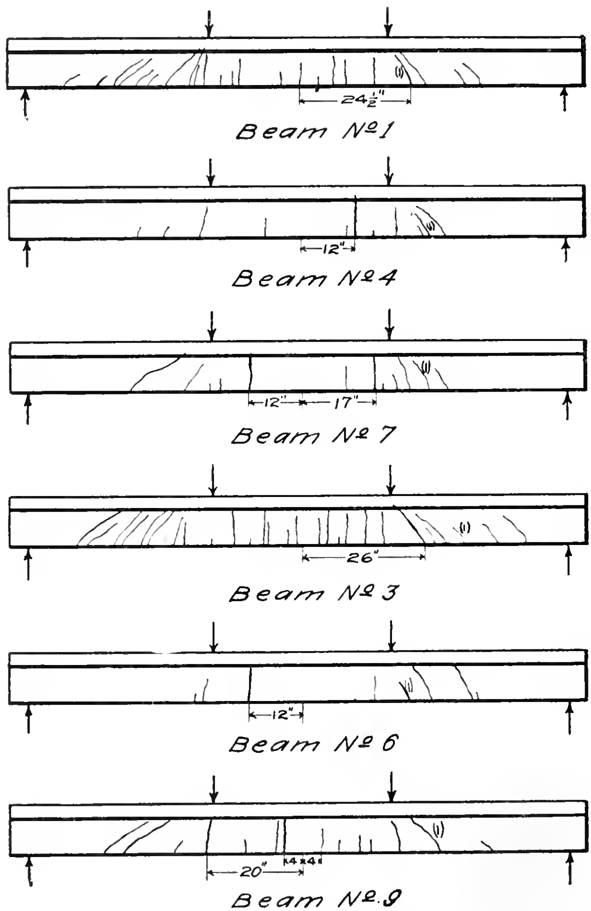


FIG. 5. SKETCH OF BEAMS AFTER FAILURE.

having a similar percentage of reinforcement. When the tension in the steel reached 13 000 to 20 000 lb. per sq. in., minute vertical cracks became visible in the concrete on the lower part of the faces of the stem of the T-beam at points in the middle third of the span length. These grew more distinct as the load was increased. When the load became sufficient to strain the steel to its yield point, these cracks opened up and finally became quite large and extended up into and along the flange of the

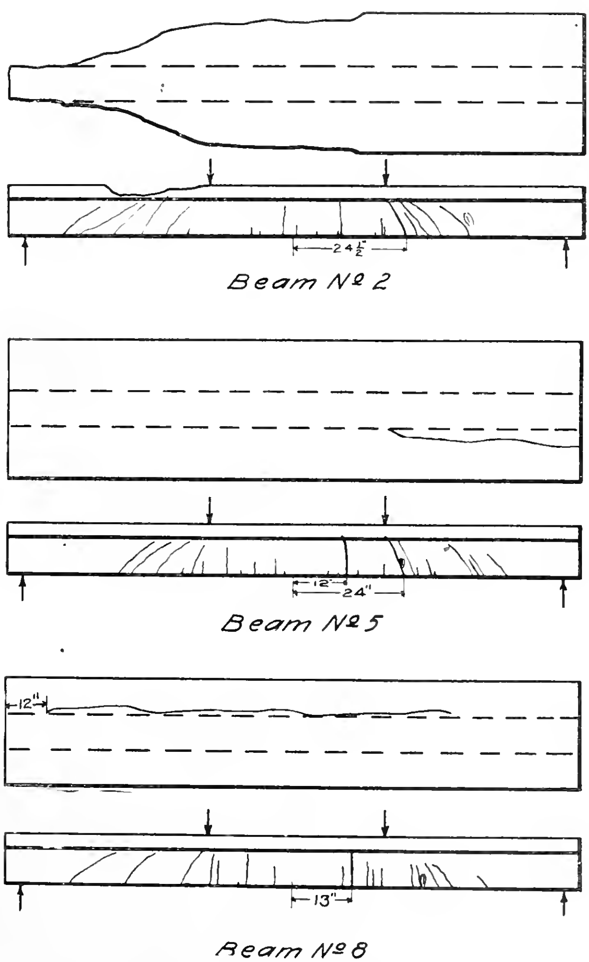


Fig. 6. Sketch of Beams after Failure.

beam. The evidences of failure by tension in the steel were apparent in every beam, as much so in those reinforced with corrugated bars as in those having plain rods.

At loads somewhat above the amounts at which it would be expected that failures by diagonal tension in the concrete would occur in beams not having metallic web reinforcement, minute diagonal cracks appeared on the face of the stem in the outer thirds of the span length. These cracks had the direction and appearance of cracks attending failure by diagonal tension. Their consideration will be taken up under "21. *Web Stresses*," (p. 26).

In general, the flanges gave no sign of failure. In one (Beam No. 2) the flange split off after the maximum load was reached, as shown in Fig. 6. In this beam there was no lateral reinforcement in the flange. It seems evident that the tearing off occurred by reason of the warping of the flange as bending took place, and as this effect was not found in the other two beams of 32-in. width, the presence of the lateral rods in the beams was probably advantageous. Such rods would, of course, be present in ordinary floor construction, and uneven bending would be resisted by this lateral reinforcement.

In the representation of diagonal and vertical cracks after the maximum load had been reached, shown in Fig. 5 and 6, the tension crack which caused failure is indicated by a heavy line. The diagonal crack first to appear is numbered 1. These diagonal cracks generally intersected the plane of the reinforcing bars at their intersection with the stirrups. The description of the action of the beams which follows is given only in sufficient detail to indicate their general behavior, though individual peculiarities of beams are also noted.

Beam No. 1.—Two tension cracks at points at the level of the reinforcing bars between the load points appeared at an applied load of 16 000 lb. Before 20 000 lb. was reached eight more tension cracks appeared in the middle third of the span length. At 20 000 lb. the first diagonal crack appeared. At 26 000 lb. it had extended to within 2 inches of the flange. With further loading a large number of diagonal cracks developed. After reaching a load of 42 000 lb., (deflection 0.5 in.), the load fell off to 41 000 lb., as the machine speed did not keep up with the deflection of the beam under the given load. The load

then slowly rose to 44 500 lb., the deflection increasing to 1.34 in. During this period the tension cracks opened up quite rapidly, while the diagonal cracks remained about the same, one diagonal crack becoming $\frac{1}{32}$ in. wide. Finally, at a deflection of 1.6 in., and an applied load of 43 800 lb., the concrete crushed at one of the load points.

Beam No. 2.—The failure of this beam was peculiar in that after it had passed the maximum load and had shown all the evidences of failure by tension of the steel, instead of holding about the same load and deflecting considerably more as the machine was run down, the final breaking was by the flanges splitting off as shown in Fig. 6. This was the only one of the three beams with 32-in. flanges which did not have lateral reinforcing rods in the flange at and near the load points. The first tension crack appeared at a point 10 in. west of the center at a load of 26 000 lb. and others appeared at 28 000 lb.

The first diagonal crack was observed 19 in. west of the west load point at 36 000 lb., and reached half-way to the flange. A number of other diagonal cracks appeared as the load was increased. At 56 000 lb. one diagonal crack had reached the flange and small horizontal cracks formed at the junction of the flange and stem. The beam carried the load well and reached a maximum of 78 300 lb. applied load. The load gradually fell off as the deflection was increased, and finally the flange on both sides from the east end to the west load point broke off suddenly, as shown in Fig. 6.

Beam No. 3.—In beam No. 3 it was noticed that each diagonal crack passed through the intersection of the stirrups and the longitudinal reinforcement. At the maximum load one of the tension cracks extended well into the flange.

Beam No. 4.—In Beam No. 4, some time after the maximum load of 29 900 lb. had been reached, the principal tension crack extended to the flange and then extended along the junction of the stem and flange, but no consequences were traceable to this. As in the other cases, the failure was by tension in the steel, followed finally by compression in the concrete.

Beam No. 5.—At an applied load of 25 000 lb., two tension cracks and one diagonal crack appeared, others following later. At 74 000 lb. the deflection curve makes an abrupt change of direction, the deflection at this load being .54 in. The tension

cracks increased in size and failure by tension in steel was evident. With increased deflection the load ran up slowly, reaching a maximum of 80 000 lb. at a deflection of 1.4 in., when one roller rolled off its bearing and one pedestal fell forward, allowing the beam to drop and break. At the maximum load there were evidences of crushing in the concrete.

Beam No. 6.—In Beam No. 6, after the maximum load of 37 000 lb. was reached the principal tension crack extended into the flange and finally extended horizontally along the junction of flange and stem. The test was then discontinued.

Beam No. 7.—In Beam No. 7, the maximum load was maintained from a deflection of .3 in. to one of 1.9 in. before final failure.

Beam No. 8.—In Beam No. 8, the maximum load was maintained from a deflection of .3 in. to one of 2.6 in. before final failure. The stress-deformation diagram gave a compressive unit deformation of .0005 at the point where the steel yielded.

Beam No. 9.—The stress-deformation curve and the deflection curve show failure by tension in the steel. The position of cracks is shown in Fig. 5.

19. *Tension in Steel.*—As already noted, the abrupt turn in the deflection diagrams (Fig. 7 to 15, following the text), taken in connection with the action of the concrete on the compressive side, indicates that the beams failed in every case through the steel becoming stressed beyond the yield point. The stress-deformation diagrams of the four beams on which observations of longitudinal deformations were made, also give marked evidence of failure by tension in the steel. In Table 5 are given the calculated stresses in the reinforcement at the maximum load, based on the formula $M = .86\ A\ f\ d$. The weight of the beam and of the loading apparatus was included in the calculations. The average stress in the reinforcement in the beams reinforced with plain mild steel rods at the maximum load is 39 800 lb. per sq. in. The average stress in the corrugated bars at the maximum load is 58 700 lb. per sq. in. It will be recalled that the average yield point for the coupons taken from the ends of the reinforcing bars was 38 300 lb. per sq. in. for the mild steel plain rods and 53 800 lb. per sq. in. for the corrugated bars. The calculated stresses at the maximum load are therefore somewhat above the average yield point of the metal. It may also be noted that

there is no marked difference in the results obtained for beams of different width of flange. The tests and calculations go to show that equation (13) may be used for calculating the resisting moment, and it is believed that this formula may properly be used at least up to a reinforcement equal to 1% of the inclosing rectangle.

TABLE 5.

RESULTS OF TESTS OF T-BEAMS.

$M = .86\ A\ f\ d.$

All failed by tension in steel.

Beam No.	Flange Width inches	Longitudinal Reinforcement Per cent	Longitudinal Reinforcement Kind	Maximum Load pounds Applied	Maximum Load pounds With Beam and Apparatus	Maximum Load pounds Per 8 inches of Width	Bending Moment M lb. -in.	Stress in Steel f lb. per sq. in.
1	16	1.05	3 ¾-in. Johnson bars	44 500	46 700	23 350	923 000	64 300
4	16	1.10	4 ¾-in. plain round	29 900	32 410	16 200	631 000	41 500
7	16	1.10	4 ¾-in. plain round	27 300	30 100	15 050	579 000	38 100
3	24	0.93	4 ¾-in. Johnson bars	53 500	55 700	18 570	1 107 500	57 500
6	24	0.92	{5 ¾-in. plain round 2 bars bent up	36 800	39 300	13 100	773 500	40 700
8	24	0.92	{5 ¾-in. plain round 2 bars bent up.	37 300	40 100	13 370	783 500	41 200
2	32	1.05	6 ¾-in. Johnson bars	78 300	80 500	20 120	1 608 000	55 700
5	32	1.05	{6 ¾-in. Johnson bars 2 bars bent up. (6 transverse bars in flange)	80 800	83 300	20 820	1 658 000	57 400
9	32	0.97	{7 ¾-in. plain round 3 bars bent up. (6 transverse bars in flange)	48 100	50 900	12 720	1 004 000	37 600

20. *Compression in Concrete.*—The stress-deformation diagrams obtained in four beams show clearly that the full compressive strength of the concrete was not developed when the yield point of the beam was reached, the amount of shortening being about .0005. The fact that the final deflection of the beam generally was several times as much as that at the yield point of

the beam shows that with the stretch of the steel beyond the yield point the neutral axis must have risen very much before final or ultimate failure by crushing of the concrete occurred, and this corroborates the preceding statement. The results bear out the assertion that beams with 1% reinforcement will have only a part of the compressive strength of the concrete developed, even when steel of 54 000 lb. per sq. in. yield point is used. As in T-beams having a width of flange equal to four times the thickness of the stem a 1% reinforcement (4% of the stem area) is very large, it does not seem that the compressive strength of the concrete in the upper fiber may be expected to be a controlling element in floor construction of this kind.

21. *Web Stresses.*—Rectangular beams which do not have metallic web reinforcement and in which the longitudinal bars are laid horizontally may be expected (for concrete of this quality) to fail by diagonal tension when the calculated vertical shearing unit stresses reach, say, 120 lb. per sq. in., provided, of course, the amount of reinforcement and relation of depth to length of span are not such that failure by tension or compression will occur before this amount of stress is developed. This is on the assumption that the method of calculation given on page 10 is applicable to T-beams so reinforced. For the T-beams tested, no matter what the width of flange, the load which would produce failure by diagonal tension in the concrete calculated in this way would be 17 000 lb. As all beams failed by tension in the steel and as the loads ran as high as 80 000 lb. it is apparent that the metallic web reinforcement was efficient and adequate.

The conditions of testing were not favorable for determining the time of appearance of the first diagonal cracks (the minute cracks which appear in the outer third of the span length and which in beams without metallic web reinforcement presage early and sudden failure), and in some cases these may have appeared before their presence was noted. However, the load at which their existence was observed is given in Table 6. In Beam No. 7 the load for the first visible crack, 18 000 lb., gives by equation (18) a value of the vertical shearing unit stress of 147 lb. per sq. in., not much above that at which a beam without metallic web reinforcement would fail. The general average time of observation of the first visible diagonal crack corresponded to a value of about 180 lb. per sq. in. This higher value of v may

be an indication that the stiffness of the stirrups holds back the growth of cracks of the size at which they become visible or even that the stirrups act with the concrete in taking these secondary stresses up to the load where the cracks become visible, or else that the method of calculation gives too high results.

After the diagonal cracks have appeared, it must be considered that the secondary tensile stresses are taken mainly or wholly by the metallic reinforcement. In Table 6 are given the values of the vertical shearing unit-stresses for the maximum loads, calculated by equation (18). As in no case was there a

TABLE 6.

WEB STRESSES.

Beam No.	Flange Width inches	At First Diagonal Crack: Load in Pounds, Applied	At First Diagonal Crack: Load in Pounds, Including Beam and Apparatus	At First Diagonal Crack: v lb. per sq. in.	At Maximum Load: Bond, u lb. per sq. in.	At Maximum Load: Shear, v lb. per sq. in.
1	16	20 000	22 200	161	302	340
4	16	29 900	32 100	234	200	236
7	16	18 000	20 200	147	186	219
3	24	28 000	30 500	222	270	405
6	24	20 000	22 500	164	194	286
8	24	27 000	29 500	214	198	292
2	32	36 000	38 800	282	260	585
5	32	35 000	37 800	275	269	605
9	32	32 000	34 800	253	180	370

failure by diagonal tension, we are most interested in the beams which carried the highest loads and hence developed the greatest shearing unit-stresses. Beam No. 2 developed 585 lb. per sq. in. and beam No. 5, 605 lb. per sq. in. These results are several times as great as the values obtained with rectangular beams without metallic reinforcement which failed by diagonal tension of the concrete.

The stresses in the stirrups may be calculated tentatively by the method given under "7. *Web Stresses*", (p. 9). For a load of 80 000 lb., $V = 40\,000$ lb.; $v = 580$. For the width of stem of 8 in. and stirrups 6 in. apart the tension in each prong of the stirrups,

calculated in this way, will be 13 900 lb., equivalent to 55 500 lb. per sq. in. The bond developed is also very high.

In the foregoing discussion the horizontal and vertical shearing stresses have been used as a means of comparing resistances to diagonal stresses. Viewed by themselves, they are also interesting. 600 lb. per sq. in. is evidently well below the actual shearing resistance of concrete, but it is considerably above the values given as the ultimate shearing strength of concrete by those who hold that shearing strength is but little more than the tensile strength of concrete.

22. *Beam Deflection.*—Considering the beams all as rectangular beams having the full section of the inclosing rectangle and as having reinforcement equal to 1% of this rectangle, the deflection in beams of different width of flange should be the same at loads proportional to the flange width. That is, a load of 10 000 lb. on a rectangular beam 8 in. wide, one of 20 000 lb. on a T-beam with flange 16 in. wide, one of 30 000 lb. on a T-beam with 24-in. flange, and one of 40 000 lb. on a T-beam with 32-in. flange, all having 1% reinforcement, should, on this assumption, give the same deflection. However, the T-beams do not have the full compressive area just above the neutral axis. As the concrete on the tension side of the neutral axis also adds to the stiffness of the beam, especially in the part in the outer thirds of the span length, the narrow width of the stem will detract from the stiffness of the beam. It may be expected, then, that the deflection of the T-beams will increase somewhat as the width of flange increases, when compared on the basis of loads proportional to the width of flange or on the basis of a load which gives the same stress in the steel. In Table 7 are given the deflections of the beams for loads which give a stress of 35 000 lb. per sq. in. in the steel, as calculated by the formula, $M = .86\ A\ f\ d$. The results average .27 in. for the 16-in. flange, .27 in. for the .24-in. flange, and .32 in. for the 32-in. flange. The decrease in stiffness for the wide flange, while apparent, is not very great.

23. *Position of Neutral Axis.*—Little can be said here concerning the position of the neutral axis except that the data and analysis go to confirm the statement that for ratios of width of flange to width of stem not exceeding those used in the experiments, the position given by considering the T-beam as a rectangular beam of the full section of the inclosing rectangle is

sufficiently close for purposes of ordinary calculation. The stress-deformation diagrams for the beams on which observations were made, so far as these results may be used, also corroborate this view. As the compressive stresses in T-beams will generally be low, the error in any use of the assumed inclosing rectangle likely to be made will be small enough to be neglected, especially if we

TABLE 7.

DEFLECTIONS FOR A STRESS OF 35 000 LB. PER SQ. IN. IN THE STEEL.

$M = .86\ A\ f\ d.$

Beam No.	Flange Width inches	Per cent Reinforcement	Applied Load pounds	Deflection inches
1	16	1.05	25 200	0.24
4	16	1.10	26 500	0.25
7	16	1.10	26 500	0.31
Av.				0.27
3	24	0.93	33 600	0.25
6	24	0.92	33 200	0.27
8	24	0.92	33 200	0.28
Av.				0.27
2	32	1.05	50 500	0.31
5	32	1.05	50 500	0.31
9	32	0.97	46 700	0.34
Av.				0.32

limit the use to the condition that the flange shall extend two-thirds of the distance to the neutral axis.

24. *Applicability of Results.*—The tests are not numerous enough or sufficiently diversified to show that the results are generally applicable to beam construction. It seems clear, however, from the general behavior of these beams that for calculations on strength the T-section may be considered to be the equivalent of rectangular beams of the size of the inclosing rectangle for widths of flange equal at least to four times the width of stem. It seems probable that this relation may be applicable to even greater widths of flange. However, the actual value of this limit cannot be of great practical importance, since a greater width would not materially change the value of the calculated resisting moment (considering it based upon tensile strength of steel and moment arm measured to center of compressive stress), and since the amount of steel will at any rate

be limited by the space in the stem and by practical considerations in placing and bedding it to an amount which will keep the maximum compressive stress within a reasonable limit.

The method of calculating the tension in the stirrups is used tentatively and is not regarded as a final method for use. It is probable that experiments will show that a different method of calculation should be adopted. The efficacy of stirrups of this kind is well brought out, but at the same time, it should be noted that the size, spacing, and bonding of the web reinforcement are of larger capacity than is usually given. The fact that all the beams, and especially the wide beams, escaped failure by diagonal tension is of especial importance.

Nothing in the observed phenomena of the tests indicates that there was an appreciable distortion from a plane cross section even in the flanges of the beam. The tearing of the flange in one beam was evidently due to unequal bending and seems not to be traceable to shear or to variations from a plane cross section.

25. *Summary.*—The following summary of the discussion is given:

1. Beams of flange width of two, three, and four times the width of stem or web and reinforced in each case with steel equal to 1% of the inclosing rectangle exhibited in a common way the characteristics of rectangular beams, and the critical failure in every case came through the longitudinal reinforcement becoming stressed beyond its yield point.

2. The full compressive strength of the concrete at the most remote fiber was not developed at the yield point of the beam, even in the beams which were reinforced with steel of 54000 lb. per sq. in. yield point.

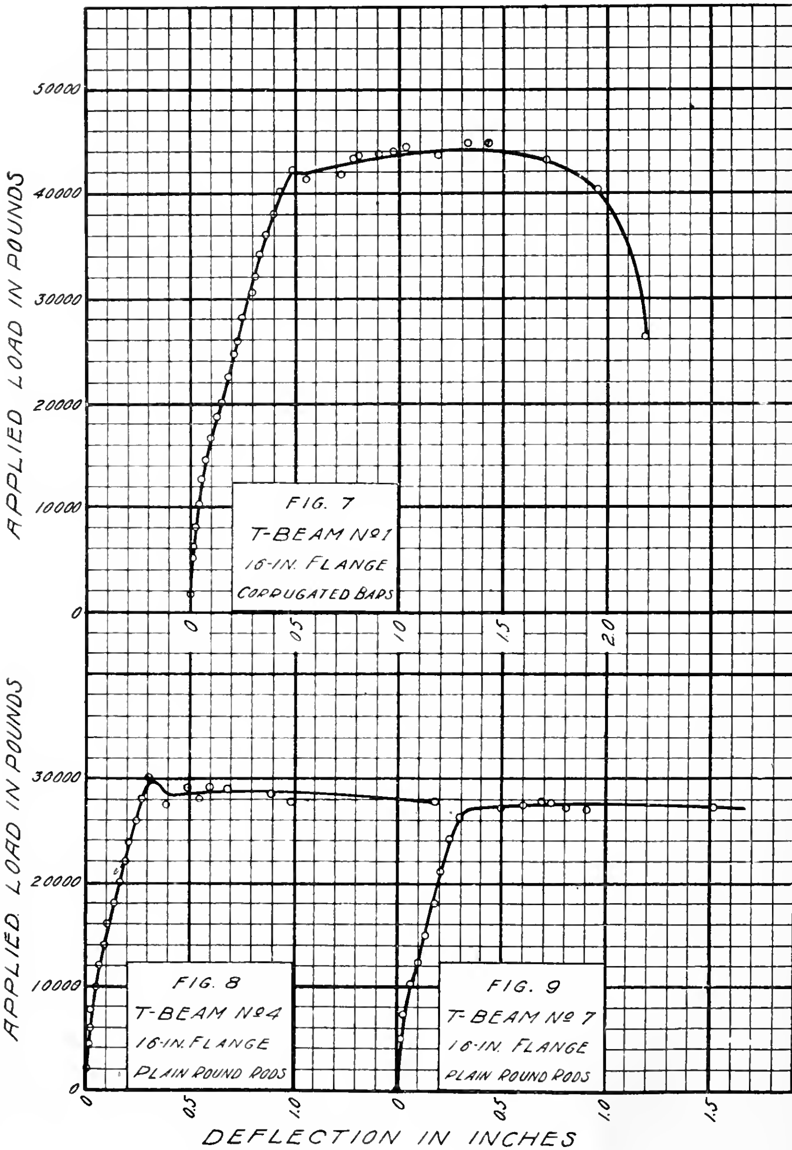
3. The beams with the wide flanges were deflected somewhat more than the narrower beams, as may be expected from the lack of full width of concrete on both the compression and the tension sides of the neutral axis, the deficiency affecting the stiffness of the beam but having little effect upon its strength at points of maximum bending moment.

4. The vertical stirrups used proved to be very effective web reinforcement. The diagonal tension cracks appeared at or above the loads at which failure by diagonal tension may be expected in beams without web reinforcement. A high resistance

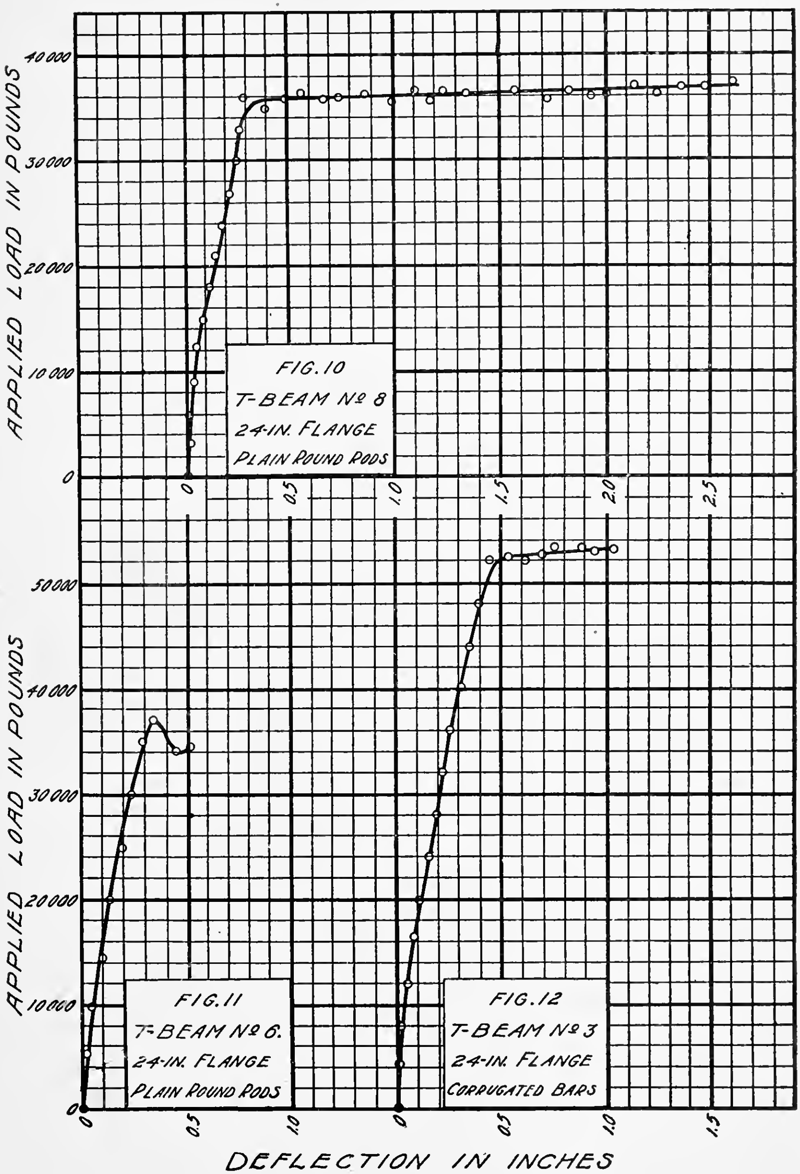
to diagonal tensile stresses was developed, as measured by the calculated maximum vertical shearing unit-stress, which in one beam was 605 lb. per sq. in. Since no beam failed by diagonal tension, the limit of strength of the web reinforcement was not determined.

5. The observed phenomena of the tests give no indication of distortion from a plane cross section and there was no indication that the thin flange was an element of weakness. The tearing of the flange of one beam after the maximum load was reached was due to causes which would not exist in a floor system as usually constructed. It seems clear that the limit of useful width of flange was not reached in the beams tested.

6. The maximum strength of T-beams to resist horizontal tension and compression (flange stresses) may well be calculated by using the ordinary methods and formulas in use for rectangular beams and considering the inclosing rectangle of the T-beam to be the equivalent rectangular beam. This approximation is at least applicable for reinforcement not exceeding 1% of the inclosing rectangle. It gives little error when the thickness of flange is at least one quarter of the depth of beam and the width of flange not more than four times the width of stem, and may be used for an even greater range without great error. The inclusion of a greater width of flange than four times the width of stem would not materially change the calculated strength of the beam, since the amount of steel which may be put into the stem is usually limited by considerations which of themselves will hold the compressive stresses within proper limits, and since the moment arm of the horizontal couple will not change much with an increase in width of flange. The web stresses, which here are very important, will differ from those found for rectangular beams, and for T-beams the actual width of stem must be used in the calculations for vertical shear and diagonal tension.



APPLIED LOAD IN POUNDS
50000
40000
30000
20000
10000
0
FIG. 7
T-BEAM No 1
16-IN. FLANGE
CORRUGATED BARS
0
0.5
1.0
1.5
2.0
APPLIED LOAD IN POUNDS
30000
20000
10000
0
FIG. 8
T-BEAM No 4
16-IN. FLANGE
PLAIN ROUND RODS
FIG. 9
T-BEAM No 7
16-IN. FLANGE
PLAIN ROUND RODS
0
0.5
1.0
0
0.5
1.0
1.5
DEFLECTION IN INCHES


APPLIED LOAD IN POUNDS
40 000
30 000
20 000
10 000
0
FIG. 10
T-BEAM Nº 8
24-IN. FLANGE
PLAIN ROUND RODS
0
0.5
1.0
1.5
2.0
2.5
50000
40 000
30 000
20000
10000
0
FIG. 11
T-BEAM Nº 6.
24-IN. FLANGE
PLAIN ROUND RODS
FIG. 12
T-BEAM Nº 3
24-IN. FLANGE
CORRUGATED BARS
0
0.5
1.0
0
0.5
1.0
1.5
DEFLECTION IN INCHES

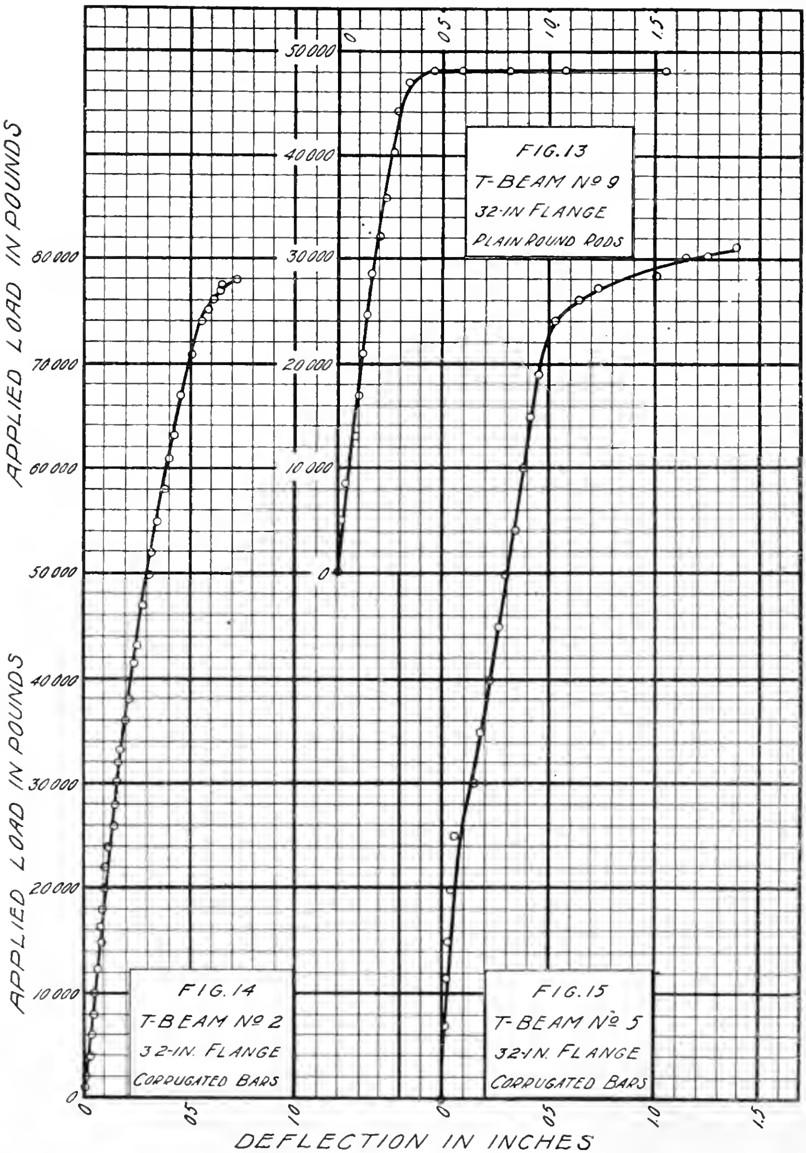


FIG. 13
T-BEAM No 9
32-IN FLANGE
PLAIN ROUND RODS
FIG. 14
T-BEAM No 2
32-IN. FLANGE
CORRUGATED BARS
FIG. 15
T-BEAM No 5
32-IN. FLANGE
CORRUGATED BARS
APPLIED LOAD IN POUNDS
APPLIED LOAD IN POUNDS
DEFLECTION IN INCHES
0
10 000
20 000
30 000
40 000
50 000
60 000
70 000
80 000
0
0.5
1.0
1.5

Publications of The Engineering Experiment Station

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

Bulletin No. 10. Tests of Plain and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.

Bulletin No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 13 NOVEMBER, 1906

AN EXTENSION OF THE DEWEY DECIMAL SYSTEM OF CLASSIFICATION APPLIED TO ARCHITECTURE AND BUILDING

by

N. CLIFFORD RICKER, D. ARCH., PROFESSOR OF ARCHITECTURE

INTRODUCTION

The Dewey Decimal Classification was invented and introduced by Dr. Melvil Dewey, also the originator of the schools for the training of librarians and their assistants. Several successive and much extended editions of his book have appeared, and the system has been found so convenient for practical uses that it is now more commonly employed in America and Europe than are any competing systems of arrangement.

All science, arts, literature, and tangible objects to be classified are distributed into ten classes or centuries:

0 to 100	General Works
100 to 200	Philosophy
200 to 300	Religion
300 to 400	Sociology
400 to 500	Philology
500 to 600	Natural Science
600 to 700	Useful Arts
700 to 800	Fine Arts
800 to 900	Literature
900 to 1000	History

Each one of these primary classes or centuries is next divided into ten secondary divisions or decades, like that for the Fine Arts:

700	Fine Arts
710	Landscape Architecture
720	Architecture
730	Sculpture
740	Drawing
750	Painting
760	Engraving
770	Photography
780	Music
790	Amusements

Each secondary class or decade is further divided into ten subdivisions or units, for example, like Architecture:

720	Architecture
721	Construction
722	Ancient
723	Mediæval
724	Modern
725	Public
726	Religious
727	Educational
728	Residence
729	Design

In this manner are obtained 1000 unit divisions, which form a system usually found sufficient for a small library, a collection of general memoranda, or a series of notes and clippings of moderate extent. But a specialist requires a much more extended subdivision of perhaps only a few of these units comprising the topics in which he is chiefly interested. This introduces a very useful property of the decimal system, namely, that it may be almost infinitely extended in any part by the subdivision of certain units without affecting others or requiring any rearrangement of the general system.

First subdivide into tenths of the unit, like Modern Architecture, for example:

724.	Modern Architectire
.1	Renaissance

.2	Grecian revival
.3	Gothic revival
.4	Tudor revival
.5	Queen Anne
.6	Neo Grec
.7	Swiss revival
.8	Romanesque revival
.9	Other modern styles

If one is particularly interested in the comparative study of the various types of the Renaissance style found in different countries, it will be convenient to subdivide 724.1 into hundredths, for example:

724.1	Renaissance
.11	Scotland
.12	England
.13	Germany
.14	France
.15	Italy
.16	Spain
.17	Russia
.18	Scandinavia
.19	Minor countries

A collection of notes and memoranda or photographs of Italian Renaissance buildings may then be so large, that it may profitably be subdivided into thousandths of the unit, as follows:

724.15	Renaissance in Italy
.151	Cinquecento
.152	High Renaissance
.153	Decadence
.154	Barocco
.155	Rococo

This would evidently arrange the materials most conveniently for a thorough study of the Italian Renaissance style in the order of its historical development. Therefore it is sufficiently evident that the decimal system of classification is capable of unlimited extension in any of its parts.

To apply the system to a collection of books, memoranda, or other materials, each particular item is simply numbered as indicated by the decimal classification. The collection is then arranged in numerical sequence, which places the objects classified in the same order. Persons not accustomed to the use of the decimal system of classification may at first find some difficulty in finding the proper number for a particular object or article. Therefore an alphabetically arranged index of the more important topics and their numbers has been added for their convenience.

It is believed that this extension of the Dewey Decimal Classification will be found useful and convenient by architects, builders, engineers and all other persons practically or theoretically concerned with Architecture and Building. Most of it has been in use for many years in the department of Architecture of this University for classifying extensive collections of lantern slides, photographs, a card index to architectural periodicals, and other materials for instruction. As meriting careful attention, the following points are suggested:

1. The suggested classification of all materials relating to each one of the architectural styles together, in order to bring them into the most compact and convenient arrangement for the student of the History of Architecture.

2. The careful separation of 690, Building Materials and Trades; 721, Architectural Construction; and 729, Architectural Forms and Design, making it now easy to assign any topic to its proper place.

TABLE
OF
CLASS NUMBERS

---

690 Building Materials Trades

See 721 for Architectural Construction.
See 729 for Architectural Forms or Design.

.1 **Theories of construction**
.11 Systems of construction

.2 **Compends**
.21 Manuals
.22 Handbooks
.23 Recipes, collections of

.3 **Dictionaries**
.31 Cyclopedias

.4 **Essays**
.41 Lectures
.42 Discussions

.5 **Periodicals**
.51 Daily
.52 Weekly
.53 Monthly
.54 Quarterly
.55 Annual

.6 **Societies; Proceedings**
.61 Trade unions
.62 Exhibitions
.621 Materials
.622 Methods
.623 Construction

690.7 **Education and study**
.71 Training of workmen
.72 Apprenticeship
.73 Tools and their uses
(See special trade for special tools.)
.74 Shop practice
.75 Trade schools
.76 Manual training

.8 **Museums**
.81 Collections
.82 Patents
.83 Inventions
.84 Machines for manufacturing
.841 Wood
.842 Stone
.843 Steel and iron
.844 Bricks
.845 Tiles
.846 Cement and lime
.847 Concrete
.848 Asphalt
.849

.9 **History of Building Materials**
.91 Ancient
.92 Mediæval
.93 Renaissance
.94 Modern
.95 History of building construction
.96 Ancient
.97 Mediæval
.98 Renaissance
.99 Modern

691 **Materials Processes Preservatives**

See 620.1 for Strength of Materials.
See 693 to 699 for Uses of Prepared Materials.

.1 **Woods**
.11 Hard conifers
.111 Pine, longleaf
.112 Pine, hard

691.113 Pine, yellow
.114 Pine, Norway
.115 Pine, pitch
.116 Tamarack; hackmatack
.117
.118 Yew
.119

.12 Soft conifers
.121 Pine, white
.122 Pine, shortleaf
.123 Cedar, white
.124 Cedar, red
.125 Hemlock
.126 Spruce
.127 Fir
.128 Cypress
.129

.13 Hard leaf woods
.131 Oak
.132 Beech
.133 Sycamore
.134 Maple, sugar
.135 Ash
.136 Hickory
.137 Walnut, black
.138 Locust
.139

.14 Soft leaf woods
.141 Poplar
.142 Gum
.143 Birch
.144 Maple, white, red
.145 Basswood; linden
.146 Elm
.147 Catalpa
.148 Butternut
.149

.15 Defects of woods
.151 Sapwood
.152 Shakes; cracks
.153 Spots; streaks
.154 Knots
.155 Decay
.156 Stains
.157 Pitch
.158 Shrinkage
.159

691.16	Injuries to woods
.161	Wet rot
.162	Dry rot
.163	Ants
.164	Borers
.165	Fungus
.169	
.17	Preservation of woods
.171	Painting
.172	Oiling
.173	Creosoting
.174	Zincking
.175	By corrosive sublimate
.176	By crude kerosene
.177	By fireproof paint
.178	By sulphate copper
.179	
.2	**Stone Material Protection**
.211	Limestone
.212	Marble
.213	Gypsum
.214	Bedford; Oolite
.221	Granite
.222	Syenite
.223	Porphyry
.231	Sandstone, ordinary
.232	Sandstone, brown
.233	Sandstone, portage
.24	Slate
.251	Serpentine
.252	Soapstone
.253	Talc
.261	Trap
.262	Basalt
.271	Tufa
.272	Travertine
.273	Peperino
.28	Other building stones
.29	Preservation
.291	By painting
.292	By oiling
.293	By paraffine
.294	By silicate of soda
.295	By glue and tannin
.296	By cement wash
.299	

691.3 Stone, artificial Concrete
.31 Beton coignet
.32 Ransome
.33 Hollow block
.34 Selenitic
.35 Lime concrete
.36 Cement concrete
.39 Aggregate

.4 Bricks Tiles Ceramic products
.41 Bricks, ordinary
.42 Bricks, pressed
.43 Bricks, moulded
.44 Bricks, glazed or enameled
.45 Bricks, self-colored
.46 Tiles
.461 Roofing
.1 Spanish
.2 Ludovici
.3 Celadon
.4 Ornamented
.9
.462 Flooring
.1 Self-colored
.2 Inlaid
.3 Embossed
.4 Glazed
.9
.463 Wall tiles
.1 Self-colored
.2 Inlaid
.3 Embossed
.4 Glazed
.5 Picture
.6 Paience panels
.7 Mouldings
.8 Painted
.9
.47 Hollow structural tiles
.471 Floor
.1 Side arch
.2 End arch
.3 Mixed arch
.9

691.472 Roof and ceiling tiles
.1 Book tiles
.2 Ceiling plates
.9
.473 Wall tiles
.1 Wall linings
.2 Bond courses
.3 Partition
.48 Terra cotta
.481 Manufacture
.482 Face blocks
.483 Bands and mouldings
.484 Columns and pilasters
.485 Cornices
.486 Ornamental
.49 Sewer tiles
.491 Salt-glazed
.492 Drain tiles
.493 Fittings
.499

.5 Lime Cement Plaster
.51 Lime, ordinary
.52 Lime, hydraulic
.53 Lime, selenitic
.54 Cement, natural
.55 Cement, portland
.56 Plaster of paris
.57 Keene's cement
.58 Hard plaster
.59

.6 Glass
.61 Window
.62 Plate, rough Rolled
.63 Plate, polished
.64 Luxfer prism, etc.
.65 Sidewalk lights
.66 Moulded
.67 Cathedral
.68 Stained
.69

691.7 Iron Steel Anti-rust processes

.71 Cast iron
.72 Malleable cast iron
.73 Wrought iron
.74 Steel, blister or tool
.75 Steel, crucible
.76 Steel, bessemer
.77 Steel, open hearth
.79 Protection of iron and steel
.791 Painting
.792 Tinning
.793 Zincking (galvanizing)
.794 Electroplating
.795 Bower-Barff process
.796 Cement coating
.797
.798
.799

.8 Other metals

.81 Copper
.82 Brass
.83 Zinc
.84 Lead
.85 Aluminum
.86 Bronze
.87 Tin
.88
.89

.9 Other materials

.91 Mineral wool
.921 Hair
.922 Jute fiber
.923 Hemp fiber
.93 Paper
.931 Sheathing
.932 Cabot's quilt
.933 Slating
.934 Roofing
.94 Fabrics woven
.941 Duck

691.942 Burlap
.943 Carpets
.944 Rugs
.945 Linings
.95 Asbestos
.951 Pipe coverings
.952 Hot air insulation
.953 Fire protection
.961 Asphalt, Trinidad
.962 Asphalt, rock
.963 Pitch
.964 Resin
.965 Coal tar
.966 Tar
.967 Damp-proof felt
.969
.97 Felt, roofing
.98 Linoleum
.99

692 Plans Specifications Estimates

.1 General drawings
.11 Plan, location
.12 Plan, foundation
.13 Plans, floor
.14 Plan, roof
.15 Elevations
.151 Front
.152 Side
.153 Rear
.154 Court
.159
.16 Sections
.161 Longitudinal
.162 Cross
.169
.19 Other general drawings

.2 Detail drawings
.21 Masonry
.211 Stone-cutting
.212 Stone-setting
.213 Marble

692.214	Tiles
.215	Slate
.216	Brickwork
.217	Bricks, ornamental
.218	Terra cotta
.219	
.22	Woodwork
.221	Carpentry
.222	Joinery
.223	Cabinet work
.224	Furniture, special
.229	
.23	Metal work
.231	Cast iron, structural
.232	Cast iron, ornamental
.233	Steel, structural
.234	Steel, ornamental
.235	Copper
.236	Tin
.237	Zinc
.238	Brass
.239	
.24	Plumbing
.241	Water supply
.242	Sanitary fixtures
.243	Drainage
.249	
.25	Heating and ventilating
.251	Furnaces
.252	Steam
.253	Hot water
.254	Gas
.255	Electric
.256	Combination systems
.257	
.258	Ventilation, natural
.259	Ventilation, forced
.26	Plastering
.261	Plain
.262	Ornamental
.263	Stucco work
.269	
.27	Roofing
.271	Gutters
.272	Leaders

692.28 Glass work
.281 Stained
.282 Beveled
.289
.29 Other drawings

.3 Specifications
.31 General conditions
.32 Excavation and grading
.33 Masonry
.331 Stonework
.332 Brickwork
.333 Terra cotta
.334 Concrete, plain
.335 Concrete, reinforced
.34 Carpentry
.341 Carpentry proper
.342 Joinery
.343 Cabinet work
.35 Metal work
.351 Cast iron
.352 Wrought iron
.353 Steel
.354 Copper
.355 Tin
.356 Ornamental
.357 Bronze
.359
.36 Plastering
.37 Painting and glazing
.371 Painting
.372 Glazing
.373 Finishing
.38 Plumbing
.39 Other specifications
.391 Lighting
.392 Heating
.393 Ventilation
.399

.4 Contracts Bids Advertisements
.41 Advertisements
.42 Bids
.43 Agreements, informal

692.44 Contracts, signed
.441 Sealed
.442 Guaranteed
.443 Variations
.444 Arbitration
.45 Bonds, security
.49

.5 Estimates Quantities Cost
.51 Methods of estimate
.52 Volume
.53 Area
.54 Units
.55 Quantities, priced
.56 Comparison
.57 Classification of data
.58
.59

.6 Superintendence
.61 Occasional
.62 Architect's stated
.63 Constant
.64 Clerk of works
.65 Special
.69

.7 Supervision of accounts
.71 Bookkeeping, system of
.72 Approval of bills
.73 Oversight of payments
.74 Statements to owner
.75 Reserved payments
.76 Extras and omissions
.77 Settlement, final
.79

.8 Professional services Fees Commissions
.81 Services, ordinary
.82 Services, extra
.83 Services, special

692.84 Rates of commission
.85 Account of payments
.86 Expenses, extra
.87 Bye commissions
.89

.9 Building laws Liabilities of architects, owners, and contractors
.91 General or state laws
.92 City ordinances
.93 Town or village ordinances
.94 Other laws
.95 Liabilities of architects
.96 Liabilities of owners
.97 Liabilities of contractors
.98 Lien laws
.99

693 Masonry Plastering Fire-proofing

.1 Stone construction

See 515.8 for Stereotomy
See 736 for Stone Carving

.11 Bonds
.12 Stonecutting
.13 Stonesetting
.14 Stone tools
.19

.2 Brick construction
.21 Bonds
.22 Adobes
.23 Cut or rubbed
.24 Ornamental
.25 Polychrome
.26 Tools
.29

.3 Terra cotta construction
.31 Setting
.32 Anchoring
.33 Backing

693.4 **Hollow tile and porous terra cotta**
.41 Walls
.42 Floors
.43 Roofs
.44 Partitions
.45 Linings
.49

.5 **Concrete and beton construction**
See 693.3 for Reinforced Concrete
.51 Massive
.52 Layers
.53 Hollow block
.54 Sidewalks
.55 Ornamental
.56 Surface finish
.59

.6 **Plastering**
.61 External
.62 Internal
.63 Ornamental
.64 Scagliola
.69

.7 **Reinforced concrete**
.71 Systems of construction
.711 Ordinary round rods
.712 Ransome
.713 Unit
.714 Hennebique
.715 Roebling
.716 Thacher
.719
.72 Forms and centers
.73 Testing and inspection
.74 Data from experiments
.75 Formulas
.76 Applications, special
.79

693.8 Fire-proofing

.81 Systems

.811 Hollow tiles

.812 Porous terra cotta

.813 Brickwork

.814 Concrete

.815 Wood and sheet metal

.816 Mortar

.819

.82 Walls and partitions

.83 Floors

.84 Roofs

.85 Columns

.86 Girders

.87 Trusses

.88 Vaults

.89

.9

694 Carpentry Joinery Cabinet-Work Stairbuilding

.1 Wood construction in general

.2 Framing and joints

.3 Strengthened beams

.4 Posts and columns

.5 Paneled and lattice construction

.6 Joinery in general

.7 Cabinet work

.8 Stairbuilding

.9

695 Roofing

.1 Shingle

.2 Slate

.3 Tile

695.4 **Metal**
.41 Tin
.42 Copper
.43 Lead
.44 Zinc

.5 **Iron or steel**

.6 **Asphalt**

.7 **Felt and gravel**
.71 Asbestos
.72 Paper

.8 **Fabrics**
.81 Duck
.82 Canvas

.9

696 Plumbing Gas and Steam Fitting

.1 **Plumbing**
.11 Piping
.12 Fixtures
.13 Tools
.19

.2 **Gas Fitting**
.21 Piping
.22 Fixtures
.23 Tools
.29

.3 **Steam Fitting**
.31 Piping
.32 Fittings
.33 Tools

.4 **Rivets and riveted joints**
.41 Tools

.5 **Screws and screw joints**
.51 Tools

696.6 **Rust or calked joints**
.61 Rust joints
.62 Calked joints

7. **Anchors Bond irons**
.71 Bond irons
.72 Anchors, wall
.73 Anchors, angle
.74 Anchors, through
.75 Anchors for gutters and leaders
.76 Anchors for masonry
.79

.8 **Other branches**

.9 **Plumbing laws and ordinances**
.91 General or state
.92 City ordinances
.93 Town or village ordinances

697 Heating and Ventilation

.1 **Fireplaces**
.11 Ordinary
.12 Ventilating

.2 **Stoves**

.3 **Furnaces, hot air**
.31 Furnaces
.32 Pipes, cold air
.33 Pipes, hot air
.34 Registers
.35 Regulators

.4 **Hot water**
.41 High pressure
.42 Low pressure
.43 Conservatory
.44 Heaters with steam supply
.45 Boilers
.46 Pipes
.47 Regulators

697.5 **Steam**
.51 High pressure
.52 Low pressure
.53 Exhaust
.54 Vacuum
.55 Boilers
.56 Pipes
.57 Regulators
.58 Air valves
.59

.6 **Gas**
.61 Illuminating
.62 Fuel
.63 Natural
.64 Acetylene

.7 **Electric and other**

.8 **Smoke flues and chimneys**
.81 Built in walls
.82 Isolated

.9 **Ventilation Ducts Fans**
.91 Natural
.92 Plenum
.93 Exhaust
.94 Fresh air ducts
.95 Foul air ducts
.96 Treatment of air
.961 Filtration
.962 Dampening
.963 Cooling
.964 Testing
.97 Regulation of air supply
.98 Fans
.981 Side fans
.982 Central fans
.99

698 Painting Glazing Finishing Paperhanging

.1 Painting Oil
.11 Lead
.12 Zinc
.13 Iron
.14 Mixed paints
.15 Oil
.16 Turpentine
.17 Dryers
.18 Tools
.19

.2 Distemper and Fresco
.21 Distemper
.22 Milk wash
.23 Cement wash
.24 Other washes
.25 Fresco, real
.26 Fresco, other methods
.27 Stencils
.28 Tools
.29

.3 Varnishing Polishing
.31 Varnish
.311 Oil
.312 Spirit
.319
.32 Shellac
.33 French polish
.34 Wax
.35 Oiling
.36 Other finishes
.37 Polishing
.38 Tools
.39

698.4 **Other modes of protection**
.41 Asphalt
.42 Tar
.43 Graphite
.49

.5 **Glazing**
.51 Puttying, ordinary
.52 Puttying, hard
.53 Cutting
.54 Setting
.55 Leading
.56 Tools
.59

.6 **Paperhanging**
.61 Paper
.62 Paste
.63 Hanging
.64 Tools
.69

.7 **Textile Hangings Tapestry**
.71 Burlap
.72 Chintz
.73 Tapestry, real
.74 Tapestry, painted
.75 Tools
.79

.8 **Relief work**
.81 Embossed paper
.82 Lincrusta
.83 Stamped leather
.84 Tools
.89

.9 **Other branches**

699 **Car and Shipbuilding**

700 Fine Arts

701 Theories Esthetics

702 Compends Manuals Outlines

703 Dictionaries Cyclopedias

704 Essays Lectures Discussions

705 Periodicals

.1 Daily

.2 Weekly

.3 Monthly

.4 Quarterly

.5 Annual

.6 Occasional

.9

706.1 Societies

.11 Painters

.12 Sculptors

.13 Illustrators

.14 Transactions

.15 Proceedings

.16 Reports

.19

707.1 Education

.11 Study

.12 Instruction

.13 Practice

708 Art Galleries and Museums

.11 Scotland

.15 Ireland

.2 England

.31 Germany

.36 Austria

708.4 France
.5 Italy
.61 Spain
.69 Portugal
.7 N. America
.71 Canada
.72 Mexico
.73 United States
.8 S. America
.9 Australia
.992 Holland
.993 Belgium
.994 Switzerland

709 History of Art in General

.3 Ancient
.311 China
.312 Japan
.313 Korea
.32 Egypt
.331 Phœnicia
.332 Philistine
.333 Judea
.334 Carthage
.335 Cyprus
.336.1 Pelasgian
.2 Etruria
.34 India
.351 Chaldea
.352 Assyria
.355 Persia
.357 Sassania
.36 Celtic
.37 Roman
.38 Greece
.39 Minor countries
.4 Modern Europe
.411 Scotland
.415 Ireland
.42 England

709.43	Germany
.431	Northern
.434	Southern
.436	Austria
.44	France
.442	Normandy
.445	Auvergne
.446	Poitou
.449	Provence
.45	Italy
.452	Lombardy
.453	Venice
.455	Tuscany
.457	Naples
.458	Sicily
.461	Spain
.469	Portugal
.47	Russia
.48	Scandinavia
.481	Norway
.485	Sweden
.489	Denmark
.49	Minor countries
.492	Holland
.493	Belgium
.494	Switzerland
.495	Modern Greece
.496	Turkey in Europe
.499	
.5	**Asia**
.51	China
.52	Japan
.54	India
.55	Persia
.59	Farther India
.6	**Africa**
.61	Northern
.62	Egypt
.63	Abyssinia
.64	Morocco
.65	Algeria
.69	

709.7	North America
.71	Canada
.72	Mexico
.728	Central America
.729	West Indies
.73	United States
.8	South America
.81	Brazil
.82	Argentina
.83	Chili
.84	Bolivia
.85	Peru
.87	Venezuela
.89	
.9	Oceanica

710 Landscape Architecture

711	Parks
712	Private Grounds
713.1	Walks
.2	Roads
.3	Drives
714.1	Lakes
.2	Streams
.3	Fountains
715.1	Trees
.2	Shrubs
.3	Hedges
.4	Vines
716.1	Plants
.2	Flowers
.3	Conservatories

716.4	Window gardens
.5	Ferneries
717.1	Arbors
.2	Summer Houses
.3	Seats
.4	Outlooks
.5	Pergolas
.6	Garden walls
.7	Niches
.8	Statues Vases
.9	
718.1	Monuments
.2	Tombs
.3	Mausoleums
719.	Cemeteries
.1	Gates
.2	Walls
.3	Walks
.4	Drives
.5	Vaults

720 Architecture

.11	Theories, general
.12	Esthetics
.13	Architectonics
.21	Compends
.22	Manuals
.23	Handbooks
.31	Dictionaries
.32	Encyclopedias

720.33 Glossaries
.34 Dictionaries of foreign terms
.41 Essays, general
.42 Lectures
.43 Articles
.44 Discussions

.5 **Periodicals**
.51 Daily
.52 Weekly
.53 Monthly
.54 Quarterly
.55 Annual
.56 Occasional

.6 **Societies**
.61 School
.62 Architects' local
.63 Draftsmen's
.64 National
.65 State
.71 Education
.72 Study
.73 Training, professional
.74 Schools, architectural
.741 Scotland
.742 England
.743 Germany
.5 Austria
.744 France
.745 Italy
.746 Spain Portugal
.747 Russia
.1 Canada
.2 Mexico
.3 United States
.8 South America
.748.1 Norway
.5 Sweden
.9 Denmark
.749

720.8 **Collections**

.81 Materials
.82 Fixtures
.83 Fittings
.84 Drawings
.85 Models
.86 Photographs
.89

.9 **History of architecture, general**
Classify under 722, 723 or 724, if possible.

.94 Europe
.941 Scotland
.5 Ireland
.942 England
.943 Germany
.1 Prussia
.2 Central Germany
.3 Bavaria
.4 South Germany
.5 Northwest Germany
.6 Austria
.7 Bohemia
.8 Poland
.9 Hungary
.944 France
.1 Brittany, etc.
.2 Normandy
.3 Isle de France
.4 Burgundy
.5 Auvergne
.6 Poitou
.7 Gascony
.8 Languedoc
.9 Provence
.945 Italy
.1 Piedmont
.2 Lombardy
.3 Venice
.5 Tuscany
.7 Naples
.8 Sicily
.9 Sardinia
.946 Spain
.9 Portugal

720.947 Russia
.1 Norway
.5 Sweden
.9 Denmark
.949 Minor countries
.2 Holland
.3 Belgium
.4 Switzerland
.5 Modern Greece
.7 Servia
.8 Roumania
.9
.95 Asia
.96 Africa
.962 Egypt
.97 North America
.971 Canada
.972 Mexico
.973 United States
.98 South America
.981 Brazil
.982 Argentina
.983 Chili
.984 Bolivia
.985 Peru
.986 Equador
.987 Venezuela
.989 Paraguay
.99 Oceanica
.993 New Zealand
.994 Australia
.999

721 Architectural Construction

See 729 for Forms and Design.
See 690, etc., for Materials, Trades, etc.

.1 Foundations
.11 Dimension stone
.12 Rubble
.13 Concrete
.131 Plain
.132 Reinforced by bars
.133 Reinforced by rails
.134 Reinforced by beams
.14 Sand or gravel

721.15 Gratings, wooden
.16 Piles
.161 Wood
.162 Sand
.163 Steel
.164 Concrete, plain
.165 Concrete, reinforced
.17. Wells, sunken
.18 Tubes, sunken
.181 Caissons, wood
.182 Caissons, steel
.19
.191 Piers, stone
.192 Piers, brick
.193 Piers, concrete
.194 Piers, concrete-steel
.195 Piers, steel-framed

.2 Walls

.211 Wood
.212 Half-timber
.22 Stone
.231 Concrete
.232 Hollow block
.233 Concrete-steel
.234 Pise (Tamped earth)
.241 Brick, solid
.242 Brick, hollow
.25 Bases, belts, etc.
.251 Base Plinths
.252 Water tables
.253 Belt courses
.254 String courses
.261 Colonnades
.1 Stone
.2 Brick
.3 Terra cotta
.4 Steel
.5 Iron
.6 Concrete
.7 Concrete-steel
.8 Wood
.262 Arcades
.1 Stone
.2 Brick

721.262.3 Terra cotta
.4 Steel
.5 Iron
.6 Concrete
.7 Concrete-steel
.8 Wood
.9
.263.1 Arcade, blind
.2 Arcade band
.3 Arched frieze
.27 Cornices
.271 Stone
.272 Brick
.273 Terra cotta
.274 Steel
.275 Iron
.276 Concrete
.277 Concrete-steel
.278 Wood
.279
.28 Pediments
.281 Stone
.282 Brick
.283 Terra cotta
.284 Steel
.285 Iron
.286 Concrete
.287 Concrete-steel
.288 Wood
.289
.29 Gables
.291 Stone
.292 Brick
.293 Terra Cotta
.294 Steel
.295 Iron
.296 Concrete
.297 Concrete-steel
.298 Wood
.299

.3 Piers Columns
.31 Wood
.311 Exposed
.312 Protected
.32 Stone

721.33 Concrete
.331 Solid
.332 Block
.333 Concrete-steel
.34 Brick
.341 Brick, cut
.342 Brick, moulded
.343 Terra cotta
.35 Metal
.351 Cast iron
.352 Wrought iron
.353 Steel
.1 Rolled Solid
.2 Riveted
.3 Latticed
.36 Fireproof Protected
.361 By mortar
.362 By hollow tiles
.363 By porous terra cotta
.364 By brickwork
.365 By concrete
.39

.4 Arched construction.

See 624.5 for Bridges.
See 729.3 for the different forms.
See 690 for Materials.

.41 Stone
.411 Dressed
.412 Rubble
.42 Brick
.43 Terra cotta
.44 Steel
.45 Cast iron
.46 Concrete
.461 Massive
.462 Hollow block
.463 Solid block
.464 Concrete-steel
.47 Wood
.48 Plaster Staff
.49

721.5 Roofs

See 695 for Roof Coverings.
See 729.35 for Forms of Roofs.

.51 Wood
.511 Sheathing
.512 Rafters
.513 Purlins
.514 Ceiling
.515 Truss Wood
.1 Types
.2 Loads
.3 Stress diagrams
.4 Dimensioning
.5 Connections
.6 Weight
.7 Cost
.8 Economy
.9

.52 Masonry

.53 Glass
.531 Glass
.532 Rafters
.533 Purlins
.534 Ceiling

See 721.515 or 721.545 for Truss.

.54 Metal
.541 Sheathing
.1 Wood
.2 Corrugated steel
.3 Lining for drip
.542 Rafters
.543 Purlins
.544 Ceiling
.545 Truss, steel or iron
.1 Types
.2 Loads
.3 Stress diagrams
.4 Dimensioning
.5 Connections
.6 Weight
.7 Cost
.8 Economy
.9

.55 Windows Openings in roofs
.551 Luthern

721.552	Dormer
.553	Skylights
.554	Scuttles
.555	Gables
.56	Roof crestings, etc.
.561	Crestings
.562	Balustrades
.563	Reliefs
.564	Statuary
.565	Cornice
.566	Bands
.57	Spires
.571	Stone
.572	Brick
.573	Terra cotta
.574	Steel
.575	Iron
.576	Concrete
.577	Concrete-steel
.578	Wood
.579	
.58	Gablets
.59	
.6	**Floors**
.61	Wood
.611	Flooring
.612	Deafening
.613	Sheathing
.614	Joists
.615	Beams
.616	Girders
.619	
.62	Stone
.621	Slabs
.622	Slabs and beams
.623	Paneled
.624	Coffered
.625	Marble
.63	Brick Tiles
.631	Brick arched
.632	Hollow tile, arched
.633	Hollow tile, flat
.634	Guastevino, arched
.64	Metal
.641	Cast Iron

721.642 Steel
.649
.65 Composite
.651 Stone and cast-iron beams
.652 Stone and steel beams
.653 Hollow tile and steel beams
.654 Porous tile and steel beams
.655 Concrete and steel beams
.656 Concrete-steel
.657 Concrete and Roebling wire Arches
.658 Concrete and expanded metal
.659
.66 Parquetry floors
.67 Mosaic
.671 Marble, plain
.672 Marble, patterns
.673 Marble, geometrical
.674 Marble, ornamental
.675 Marble and cement
.676 Inlaid concrete
.679
.68 Tiles
.681 Inlaid
.682 Self-colored
.683 Glazed
.684 Embossed
.685 Tesserae
.69
.691 Cement
.692 Artificial stone
.693 Xylolith
.694 Linoleum
.699

.7 Ceilings

See 721.4 for Construction of Vaulted Ceilings
See 729.6 for Forms of Ceilings.

.71 Wood
.711 Matched and beaded
.712 Panels planted on
.713 Beam
.714 Mill-floor system
.715 Paneled
.716 Coffered
.719

721.72 Stone
.721 Flat
.722 Beam
.723 Paneled
.724 Coffered
.73 Brick or tile and steel
.731 Flat, plain
.732 Flat, enameled
.733 Flat, ornamented
.734 Paneled
.735 Coffered
.74 Metal
.741 Cast iron with steel beams
.742 Steel trough plates and beams
.743 Steel buckled plates and beams
.744 Steel panels and beams
.745 Steel sheets on wood sheathing
.746 Steel stamped on wood ceiling
.75 Concrete Plaster
.751 Concrete, plain
.752 Concrete-steel
.753 Concrete-steel beams
.754 Concrete-steel paneled
.755 Plaster, plain
.756 Plaster, ornamental
.757 Plaster, paneled
.758 Plaster, painted
.759
.79 Other ceilings

.8 Doors Enclosures Windows

.81 Doors, wood
.811 Single
.812 Double
.813 Sliding
.814 Folding
.815 Concealed or secret
.816 Glazed
.82 Doors, metal
.821 Single
.822 Double
.823 Sliding
.824 Concealed
.825 Fire-proof
.826 Sheet metal on wood

721.827 Wire-glazed
.828 Vault
.829
.84 Windows, external
.841 Sliding
.842 Casement
.843 Fixed
.844 Wire-glazed
.845 Fireproof
.846 Leaded
.847 Transoms
.85 Windows, internal
.851 Sliding
.852 Hinged
.853 Fixed
.854 Wire-glazed
.855 Fireproof
.856 Leaded
.857 Transoms
.86 Enclosures of doors and windows
.861 Architrave
.862 Cap, horizontal
.863 Pediment on consoles
.864 Pediment on pilasters
.865 Pediment on engaged columns
.866 Pediment on free columns
.867 Lintel only
.868 Sill and stool
.869
.87 Shutters Blinds Screens Grilles
.871 Shutters, wood
.872 Shutters, steel
.873 Blinds, ordinary
.874 Blinds, Venetian
.875 Screens, fly
.876 Grilles, plain
.877 Grilles, ornamental
.88 Fastenings Locks
.881 Shutter fastenings
.882 Blind fastenings
.883 Door locks
.1 Rebated
.2 Mortise
.3 Rim
.4 Dead
.5 Latch

721.883.6 Sliding door
.7 Bolts
.8 Espagnolette bolts
.9

.89 Other fixtures
.891 Hinges, blind
.892 Hinges, door
.1 Fast
.2 Loose joint
.3 Pin
.4 Spring
.5 Self-closing
.893 Door closers
.894 Sash fasts
.895 Blind fasts
.899

.9 Iron and composite structures

See 620.1 for Strength of Materials.

Classify here only that which cannot be placed elsewhere, under 721 etc.

.91 Cast-iron structures
.92 Wrought-iron structures
.93 Steel structures
.94 Composite structures
.95 Steel and wood
.96 Steel and stone
.97 Steel and ceramic
.971 Steel and brick
.972 Steel and tile
.973 Steel and terra cotta
.98 Steel and glass
.99 Wood and glass

722, 723, 724 History of Architecture

Classify modern American buildings of importance in the History of Architecture under 724; generally all other American buildings under 725 to 728 inclusive.

Modern foreign buildings are usually placed under 724, unless of special importance as examples of the class or purpose, when they are to be treated like American buildings.

Classification of Historical Data

The following subdivision is recommended for the convenient arrangement of all data particularly referring to the History of Architecture. It is readily applicable to each subordinate or general division under 722, 723 and 724, being simply annexed to the style numbers.

.001	General
.0011	Country
.0012	Climate
.0013	History
.0014	Religion
.0015	Government
.0016	Social conditions
.0017	Character of style
.0018	Derivation of style
.0019	Influence of style
.002	Materials
.0021	Wood
.0022	Stone
.0023	Concrete
.0024	Bricks Tiles
.0025	Mortar Cement
.0026	Glass
.0027	Iron Steel
.0028	
.0029	
.003	Construction
.0031	System employed
.0032	Arch Vault Dome
.0033	Foundations
.0034	Floors
.0035	Walls Supports
.0036	Ceilings
.0037	Roofs Spires
.0038	Doors Windows
.0039	
.004	Design
.0041	Facades
.0042	Sections
.0043	Ceilings, treatment of
.0044	Roofs, forms of
.0045	Bases of buildings
.0046	Colonnades

.0047	Arcades
.0048	Cornices Belts Entablatures
.0049	Proportions, system of
.005	Decoration
.0051	Mouldings
.0052	Statues
.0053	Sculptures
.0054	Painting
.0055	Mosaics
.0056	Gilding
.0057	Furniture
.0058	Fabrics
.0059	Pottery
.006	Sanitation
.0061	Water supply
.0062	Drainage
.0063	Sewage disposal
.0064	Plumbing
.0065	Lighting
.0066	Heating
.0067	Ventilation
.0068	Burial
.0069	
.007	Buildings, kinds of
.0071	Religious
.0072	Mortuary
.0073	Memorial
.0074	Military
.0075	Residence
.0076	Public
.0077	Amusement
.0078	Engineering
.0079	
.008	Examples described
.0081	Religious
.0082	Mortuary
.0083	Memorial
.0084	Military
.0085	Residence
.0086	Public
.0087	Amusement
.0088	Engineering
.0089	
.009	Biographies
.0091	Architects
.0092	Sculptors

.0093	Painters
.0094	Art-workers
.0095	Connoisseurs
.0096	Builders
.0097	Engineers
.0098	Rulers
.0099	

722. Ancient or primitive architecture

.0 Prehistoric

.011	Scotland
.015	Ireland
.019	Wales
.02	England
.031	Germany
.036	Austria
.04	France
.051	Italy
.052	Sardinia
.053	Sicily
.061	Spain
.069	Portugal
.07	Russia
.071	Canada
.072	Mexico
.073	United States
.1	Indian
.2	Mound-builders
.3	Pueblo
.4	Cave-dwellers
.074	S. American
.075	Peru
.08	Scandinavia
.081	Norway
.085	Sweden
.089	Denmark
.09	
.091	Egypt
.092	Holland
.093	Belgium
.094	Switzerland
.095	Greece
.096	Turkey
.097	Russia
.098	N. Africa
.099	

722.11 China
.12 Japan
.13 Korea
.14 Philippine

.2 Egypt
.21 Nubia
.22 Abyssinia

.3 Phoenician, Jewish, etc.
.31 Phoenicia
.32 Philistia
.33 Judea
.34 Carthage
.35 Cyprus

.4 India, East
.41 Buddhist
.42 Jaina
.43 Himalayan
.44 Dravidian
.45 Chalukyan
.46 Indo-Aryan
.47 Burmah
.48 Siam
.49

.5 Western Asia
.51 Babylonia
.52 Assyria
.53 Persia, ancient
.54 Sassania
.61 Pelasgian
.611 Greece
.612 Asia Minor
.62 Etruria

.7 Roman
.71 Rome
.72 England
.73 Germany Austria

722.74 France
.75 Italy, except Rome
.76 Spain Portugal
.77 Asia
.78 Africa
.79

.8 **Grecian**
.81 Athens
.82 Peninsula
.83 Mainland, except Athens
.84 Archipelago
.85 Asia Minor
.86 Italy
.87 Sicily
.88 Africa
.89

.9 **Other ancient styles**

723. Mediaeval Christian Mohammedan

.1 **Early Christian**
.11 Syria
.12 England Saxon
.13 Germany Austria
.14 France
.15 Italy
.151 Rome
.152 Ravenna
.16 Coptic in Egypt
.17 N. Africa
.18 Scandinavia
.19

.2 **Byzantine**
.21 Byzantine proper
.22 Armenia
.23 Russia
.24 Bulgaria
.25 Greece
.29

723.3	**Mohammedan**
.311	Arabia
.312	Syria
.32	Egypt
.33	Persia
.34	Turkey
.35	India
.36	Spain Moorish
.37	North Africa
.38	
.39	
.4	**Romanesque**
.411	Scotland
.415	Ireland
.42	England
.431	Germany
.436	Austria
.44	France
.441	Anjou
.442	Normandy
.445	Auvergne
.446	Poitou
.449	Provence
.45	Italy
.451	Piedmont
.452	Lombardy
.453	Venice
.455	Tuscany
.457	Naples
.458	Sicily
.459	
.461	Spain
.469	Portugal
.48	Scandinavia
.481	Norway
.485	Sweden
.489	Denmark
.49	
.492	Holland
.493	Belgium
.494	Switzerland
.499	

723.5 Gothic

.511 Scotland
.515 Ireland
.52 England
.521 Early English
.522 Decorated
.523 Perpendicular
.531 Germany
.536 Austria
.537 France
.55 Italy
.552 Lombardy
.553 Venice
.555 Tuscany
.558 Sicily
.561 Spain
.569 Portugal
.58 Scandinavia
.581 Norway
.585 Sweden
.589 Denmark
.59 Minor countries
.592 Holland
.593 Belgium
.594 Switzerland
.599

724. Modern

.1 Renaissance

.111 Scotland
.115 Ireland
.12 England
.121 Elizabethan
.122 Jacobean
.123 17th Century
.124 18th Century
.131 Germany
.136 Austria
.14 France
.141 Francis I
.142 Henry IV
.143 Louis XIV
.144 Louis XVI
.145 Empire

724.15	Italy
.151	Cinquecento
.152	High Renaissance
.153	Decadence
.154	Barocco
.161	Spain
.169	Portugal
.17	Russia
.171	Canada
.172	Mexico
.173	United States
.1	Old colonial
.2	Spanish colonial
.178	South Americ
.1	Brazil
.2	Argentina
.3	Chili
.4	Bolivia
.5	Peru
.6	Ecuador
.7	Venezuela
.9	Paraguay
.18	Scandinavia
.181	Norway
.185	Sweden
.189	Denmark
.19	Minor countries
.192	Holland
.193	Belgium
.194	Switzerland
.199	
.2	**Classical revival Grecian**
.211	Scotland
.212	Ireland
.22	England
.231	Germany
.236	Austria
.24	France
.25	Italy
.261	Spain
.269	Portugal
.27	Russia
.271	Canada
.272	Mexico

724.273 United States
.278 South America
.281 Norway
.285 Sweden
.289 Denmark
.292 Holland
.293 Belgium
.294 Switzerland
.299

.3 Gothic revival
.311 Scotland
.315 Ireland
.32 England
.331 Germany
.336 Austria
.34 France
.35 Italy
.361 Spain
.369 Portugal
.37 Russia
.371 Canada
.373 United States
.381 Norway
.385 Sweden
.389 Denmark
.392 Holland
.393 Belgium
.394 Switzerland

.4 Tudor Gothic revival
.411 Scotland
.412 Ireland
.42 England
.471 Canada
.473 United States
.49

.5 Queen Anne revival
.511 Scotland
.512 Ireland
.52 England
.571 Canada
.573 United States
.59

724.6	**Neo Grec**	
.62	England	
.631	Germany	
.636	Austria	
.64	France	
.65	Italy	
.661	Spain	
.669	Portugal	
.671	Canada	
.673	United States	
.68	Scandinavia	
.69		
.7	**Half-timber**	**Swiss**
.711	Scotland	
.712	Ireland	
.72	England	
.731	Germany	
.736	Austria	
.74	France	
.75	Italy	
.761	Spain	
.769	Portugal	
.77	Russia	
.771	Canada	
.772	Mexico	
.773	United States	
.781	Norway	
.785	Sweden	
.789	Denmark	
.792	Holland	
.793	Belgium	
.794	Switzerland	
.799		
.8	**Romanesque revival**	
.811	Scotland	
.812	Ireland	
.82	England	
.831	Germany	
.836	Austria	
.84	France	
.85	Italy	
.861	Spain	
.869	Portugal	

724.871 Canada
.873 United States
.881 Norway
.885 Sweden
.889 Denmark
.892 Holland
.893 Belgium
.894 Switzerland
.899

9 Other recent styles
.911 Scotland
.915 Ireland
.92 England
.931 Germany
.936 Austria
.94 France
.95 Italy
.961 Spain
.969 Portugal
.97 Russia
.971 Canada
.972 Mexico
.973 United States
.978 South America
.1 Brazil
.2 Argentina
.3 Chili
.4 Bolivia
.5 Peru
.6 Ecuador
.7 Venezuela
.8 Paraguay
.9
.981 Norway
.985 Sweden
.989 Denmark
.992 Holland
.993 Belgium
.994 Switzerland
.999

725 Public Buildings

.1 Administration Government
.111 National capitols
.112 State capitols
.113 Provincial capitols

725.114 Houses of parliament
.115 Provincial buildings
.12 Ministries
.121 State
.122 Finance
.123 War
.124 Navy
.125 Foreign affairs
.126 Interior
.127 Education
.128 Commerce
.129
.13 City buildings
.131 City halls
.132 Town halls
.133 Guild halls (public)
.134 Office buildings
.14 Custom houses, etc.
.141 Custom houses
.142 Customs warehouses
.143 Bonded storehouses
.144 Excise offices
.15 Court houses Record offices
.151 Supreme court houses
.152 Appeal court houses
.153 Court houses
.154 Justice courts
.155 Record office buildings
.156 Archive buildings
.159
.16 Postal buildings
.161 National buildings
.162 City post offices
.163 Village post offices
.164 Railway postal cars
.165 City postal cars
.17 Official residences Palaces of rulers
.171 National
.172 State
.173 City
.18 Barracks Police buildings
.181 National barracks
.182 State barracks
.183 Armories
.184 National police buildings

725.185 State police buildings
.186 City police buildings
.19 Fire buildings
.191 Fire administration
.192 Engine houses
.193 Fire patrol
.194 Fire alarm stations

.2 Business and commercial buildings

.21 Stores
.211 Wholesale
.212 Department
.213 Retail city
.214 Retail village
.215 Warehouses, wholesale
.216 Warehouses, retail
.22 Mixed store, office and apartment buildings
.221 Stores and offices
.222 Stores and flats
.223 Offices and flats
.224
.23 Office buildings
.231 Office only
.232 Telegraph and office
.233 Insurance and office
.234 Hall and office
.24 Bank buildings
.241 Banks only
.242 Bank and office
.243 Savings banks
.244 Savings bank and office
.245 Safe deposit
.25 Exchanges Boards of trade
.251 Stock exchanges
.252 Provision exchanges
.253 Cotton exchanges
.254 Lumber exchanges
.255 Oil exchanges
.259
.26 Markets
.261 City
.262 Provisions
.263 Commission
.264 Retail

725.27 Cattle markets
.271 Stock yards
.272 Cattle
.273 Horses Mules
.274 Sheep Goats
.275 Hogs
.276 Fowls
.279
.28 Abattoirs
.281 Public
.282 Private
.283 Packing houses
.284 Storehouses
.29 Other commercial buildings

.3 Transportation and storage

.31 Railway passenger stations
.311 Country
.312 City through
.313 City terminal
.314 Union
.315
.316 Electric passenger
.317 Street-car
.318 Elevated
.319 Underground
.32 Railway freight houses
.321 Terminal
.322 Local
.323 Express
.33 Railway shops
.331 Metal
.332 Wood
.333 Painting
.334 Round houses
.335 Car barns
.336 Water tanks
.337 Storehouses
.338 Tool houses
.339
.34 Dock buildings
.341 Passenger
.342 Freight
.343 Wharf boats
.344 Wharf storehouses

725.35 Warehouses
.351 Merchandise
.352 Cold storage
.353 Ice plants
.354 Storage of furniture, etc.
.36 Grain elevators
.361 Brick
.362 Tiles
.363 Wood
.364 Concrete-steel
.365 Steel
.37
.371 Coals
.372 Ores
.373 Cement Lime Plaster
.374 Malt
.375 Sand
.39

.4 Manufactories

.41 Textile
.411 Wool
.412 Cotton
.413 Silk
.414 Linen
.415 Hemp
.416 Jute
.419
.42 Beer Alcohol, etc.
.421 Breweries
.422 Distilleries
.423 Wood alcohol
.424 Spirits turpentine
.425 Malteries
.43 Iron and steel
.431 Smelters
.432 Foundries
.433 Rolling mills
.434 Machine shops
.435 Pattern shops
.436 Nail and screw works
.437 Wire and fence works
.438 Ornamental
.439

725.44 Wood
.441 Saw mills
.442 Planing mills
.443 Cabinet mills
.444 Furniture works
.445 Agricultural works
.446 Specialty works
.449

.45 Carriage and car shops
.451 Carriages
.452 Wagons
.453 Automobiles
.454 Bicycles
.455 Car shops (contract)
.456 Locomotives (contract)

.46 Paper mills
.461 Paper
.462 Wall paper
.463 Straw board
.469

.47 Milling
.471 Flour
.472 Meal
.473 Feed

.48 Ceramic Glass Works
.481 Bricks, ordinary
.482 Bricks, pressed and moulded
.483 Terra cotta
.484 Tiles, roofing
.485 Tiles, floor
.486 Potteries
.487 Glass, window Bottles
.488 Plate
.489 Stained
.49

.5 Hospitals Asylums
.51 General
.511 Sick
.512 Surgical
.513 Eye
.514 Ear
.515 Lying-in
.516 Incurables
.517 Consumption
.518 Contagious
.519

725.52	Insane
.521	National
.522	State
.523	City
.524	Incurables
.525	Private
.53	Feeble-minded
.531	Idiots
.532	Defectives
.533	Defective diseased
.54	Blind Deaf
.541	Blind
.542	Deaf
.543	Schools
.544	Shops
.545	Colleges
.55	Almshouses
.551	National
.552	State
.553	County
.554	City
.555	Town
.556	Endowed
.557	Subscription
.558	Society
.559	
.56	Homes for aged
.561	Public
.562	Society
.563	Endowed
.564	Subscription
.565	Private
.57	Homes for children, orphans
.571	National
.572	State
.573	City
.574	Church
.575	Society
.576	Endowed
.58	Foundlings
.581	City
.582	Church
.583	Society
.584	Private
.59	Homes for soldiers and seamen
.591	National

725.592 State
.593 Society
.594 Private
.595 Widows
.596 Orphans

.6 Prisons Reformatories

.61 Penitentiaries
.611 National
.612 State
.613 City
.62 Jails
.621 County
.622 City
.623 Village
.624 Police cells
.63 Reformatories for adults
.631 Houses of correction
.632 Houses of detention
.633 Work houses
.634 Houses for women
.64 Reformatories for young
.641 Boys
.642 Girls
.643 Parental schools
.644 Truant school
.65 Asylums for inebriates
.651 Washingtonian
.652 Hospitals
.653 Drug victims
.654 Incurables

.7 Refreshments Baths Parks

.71 Cafes Restaurants
.711 Buffets
.712 Dairies
.713 Cafes
.714 Restaurants
.715 Restaurant gardens
.72 Saloons Sample rooms
.73 Baths
.731 Ordinary
.732 Medicated
.733 Turkish
.734 Russian
.735 Shower

725.736 Rain
.737 Vapor
.739
.74 Swimming baths
.741 Public
.742 Society
.743 Private
.75 Buildings for watering places
.751 Spring houses
.752 Casinos
.753 Bowling alleys
.754 Tennis courts
.755 Porticos
.76 Buildings for parks
.761 Shelters
.762 Music pavilions
.763 Kiosks
.764 Animals
.765 Plants
.766 Conservatories
.767 Refreshments
.768 Toilet
.769

.8 Recreation

.811 Music halls
.812 Concert halls
.813 Orchestra halls
.821 Theatres
.822 Marionette theatres
.823 Opera houses
.824 Vaudevilles
.831 Lecture halls
.832 Recital halls
.841 Bowling alleys
.842 Billiard halls
.843 Card halls
.851 Gymnasiums
.852 Turn halls
.853 Drill halls for boys
.86 Rinks
.861 Skating
.862 Roller skating
.863 Bicycle
.864 Running

725.87 Boat houses
.871 Club
.872 Private
.873 Public
.881 Riding halls
.882 Riding schools
.883 Bicycle halls
.89 Shooting galleries
.891 Public
.892 Military
.893 Club
.894 Society
.895 Private

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.91 Exhibition buildings
.911 International
.912 National
.913 State
.914 County
.915 City
.916 Memorial
.917 Art
.918 Antiquities
.919
.92 Halls for temporary purposes
.921 Shooting contests
.922 Musical contests
.923 Religious meetings
.924 Chautauqua assemblies
.925 Political meetings
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.93 Workingmen's clubs, etc.
.931 Clubs
.932 Institutes
.933 Unions

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.12 Assyrian
.13 Jewish
.14 Etruscan
.15 Grecian

726.16	Roman
.17	Chinese
.18	Japanese
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.2	**Mosques**
.21	Courtyard
.22	Byzantine
.23	Indian
.3	**Synagogues**
.4	**Chapels S. S. buildings**
.41	University
.42	College
.43	Asylum
.44	Memorial
.45	Cemetery
.46	Private
.47	Sunday school buildings
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.5	**Churches**
.51	Roman Catholic
.52	Protestant Episcopal
.53	Greek
.54	Methodist Episcopal
.55	Presbyterian Congregational
.56	Baptist Christian
.57	Friends
.58	Christian Science
.59	
.6	**Cathedrals**
.61	Roman Catholic
.62	Protestant Episcopal
.63	Greek
.7	**Monasteries**
.71	Abbeys
.72	Monasteries

726.73 Priories
.74 Convents
.75 Houses for clergy
.76 Paulist fathers

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.81 Chapels, cemetery
.82 Chapels, memorial
.83 Vaults, public
.84 Vaults, family
.85 Tombs, memorial
.86 Tombs, family
.87 Tombs, society
.88 Tombs, private
.89

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.91 Y.M.C.A. houses
.92 Y.M.C.A. hotels
.93 Y.W.C.A. houses
.94 Y.W.C.A. hotels

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.16 Orphans
.17 Manual training
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.2 Academies Seminaries
.21 Academies
.22 Seminaries (not professional)
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.24 Boarding schools, girls'

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.33	City
.34	Graduate
.35	Sectarian
.36	Scientific
.4	**Professional schools**
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.42	Medicine
.43	Law
.44	Normal
.441	National
.442	State
.443	City
.444	Private
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.451	Architecture
.452	Architectural engineering
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.461	Voice
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.465	Minor instruments
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.68 Private
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.7 Art galleries

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.79

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.82 State
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.863 Law
.864 Normal
.865 Engineering
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.2 Zoölogy
.3 Botany
.4 Entomology
.5 Geology
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.9

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.931 Architecture
.932 Architectural
.933 Civil
.934 Electrical
.935 Mechanical
.936 Railway
.937 Sanitary
.939
.94 Education
.941 National
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.95 Religion
.951 Ministerial
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.961 National
.962 State
.963 County
.964 City
.965 Local
.969
.99

728 Residences
.1 Tenements
.11 City, for poor
.12 City, for workers
.13 City, for clerks, etc.
.14 Country
.15 Factory
.17 Society
.19
.2 Apartment buildings
.21 Flats, small
.22 Flats, medium
.23 Flats, large
.24 Bachelor's

728.25 Women's
.26 Family
.27 Double houses
.28 Rooming houses
.29

.3 City houses
.31 Small, wood
.32 Small, brick
.33 Small, stone
.34 Medium, brick
.35 Medium, stone
.36 Mansions, inside
.37 Mansions, corner
.38 Mansions, detached
.39

.4 Buildings for clubs and societies
.41 Clubs, dining
.42 Clubs, meeting
.43 Masonic
.44 Odd Fellows
.45 Knights of Pythias
.46 Elks
.47 G.A.R.
.48 Insurance, fraternal
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.5 Hotels
.51 Country inns
.52 Village inns
.53 City, rooming
.54 City, European
.55 City, American
.56 City, largest
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.59

728.6	**Village and country homes**
.61	Small
.62	Brick
.63	Stone
.64	Concrete
.65	Plastered
.66	Masonry and wood
.67	Farm houses
.68	Cottages for laborers
.69	
.7	**Summer homes**
.71	Tents
.72	Portable
.73	Wood
.74	Brick
.75	Stone
.76	Mixed
.77	Concrete
.78	Metal
.79	
.8	**Country seats**
.81	Castles
.82	Chateaux
.83	Manor houses
.84	Villas
.89	
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.91	Gate lodges
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.922	Laborers
.923	Gardeners
.924	Grooms
.925	Coachmen
.926	Keepers
.927	Foresters
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728.93 Kitchens, laundries, etc.
.931 Kitchens
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.951 Barns, small
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.983 Conservatories
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.986 Palm houses
.987 Forcing houses
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728.99 Miscellaneous outbuildings
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.993 Fowl houses
.994 Pigeon houses
.995 Rabbit houses
.996

729 Architectural design and decoration

See 690 for Materials.
See 721 for Construction.
Classify Forms and Design here.

.1 The elevation
.11 Composition
.12 Subdivision
.13 Proportions
.14 Light and shade
.15 Perspective effect
.16 Balance
.17 Axial lines
.18 Accenting
.19 The section
.191 Longitudinal
.192 Transverse
.193 Diagonal
.194 Broken
.195 Oblique

.2 The plan
.21 Composition
.22 Distribution
.23 Proportions
.24 Sequence of rooms
.25 Communications, horizontal
.26 Communications, vertical
.27 Axial lines
.28 Balance
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.3 Elementary forms

See 721 for Construction of Forms.

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.312 Basement

729.313 Wall proper
.314 Belts String courses
.315 Bands, ornamental
.316 Polychrome
.317 Entablatures
.1 Architrave
.2 Frieze
.3 Cornice
.4 Balustrade
.318 Mansard cornices
.319

.32 Supports
.321 Piers, simple
.322 Piers, compound
.323 Orders, architectural
.1 Tuscan
.2 Doric
.3 Ionic
.4 Corinthian
.5 Composite
.324 Columns, other forms
.325 Pilasters, other forms
.326 Colonnades

.33 Arches and arcades
.331 Semicircular
.332 Segmental
.333 Pointed
.334 Horizontal
.335 Elliptical
.336 Oval
.337 Tudor
.338 Arched frieze
.339 Arcades

.34 Vaults and domes
.341 Tunnel
.342 Annular
.343 Cross
.344 Cloister
.345 Gothic, ribbed
.1 Tunnel
.2 Cross
.3 Cloister
.4 Polygonal
.5 Star
.6 Net
.7 Fan, square
.8 Fan, rectangular
.9

729.346	Helicoidal
.347	Domes, circular
.348	Domes, pendentive
.349	
.35	**Roofs Spires**
.351	Gable, roofs
.352	Hip
.353	Valley
.354	Flat
.355	Cylindrical
.356	Conical
.357	Spires
.1	Square
.2	Octagonal
.3	Round
.4	Open Tracery
.358	Gablets
.359	
.36	**Towers**
.361	Square
.362	Rectangular
.363	Polygonal
.364	Round
.365	Lanterns
.366	Turrets
.369	
.37	**Gables Pediments**
.371	Gables
.372	Gables, stepped
.373	Pediments, triangular
.374	Segmental
.375	Semicircular
.376	Polygonal
.377	Broken
.378	Mixed
.379	
.38	**Doors Windows**
.381	Doors
.1	External single
.2	External double
.3	External transom
.4	Internal single
.5	Internal double
.6	Internal transom
.7	Glazed
.8	Secret
.9	

729.382 Windows
.1 External sliding
.2 External casement
.3 External stained
.4 Staircase
.5 Tracery
.6 Internal
.7 Grille
.8 Lattice
.9

.383 Bay windows
.1 Rectangular
.2 Polygonal
.3 Circular
.4 Diagonal

.384 Oriel windows
.1 Square
.2 Rectangular
.3 Polygonal
.4 Circular
.5 Diagonal

.385 Luthern windows

.386 Dormer windows
.1 Rectangular
.2 Triangular
.3 Circular
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.5 Tracery
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.7 Blind
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.39 Stairs Balustrades
.391 External steps
.392 External ramps
.393 External staircases
.394 External balustrades
.395 Staircase towers
.396 Internal stairways
.397 Elevators
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.399

.4 Painted decorations

.41 Plant forms
.421 Animal forms
.422 Human forms
.423 Mythological forms

729.43	Grotesques
.441	Conventional forms
.442	Geometrical forms
.443	Fanciful forms
.45	Mouldings
.461	Architraves
.462	Friezes
.463	Cornices
.464	Bands
.465	Panels
.466	Cartouches
.467	Centers
.468	Borders
.469	
.47	Painted orders
.471	Simple
.472	With pedestals
.473	Pilasters
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.475	Mixed
.48	Painted ceilings and vaults
.481	Centers
.482	Panels
.483	Borders
.484	Compartments
.485	Historical
.486	Biblical
.487	Mythological
.488	Decorative
.489	
.49	Painted walls
.491	Centers
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.494	Dados
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.497	Mythological
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.499	
.5	**Relief decoration**
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.521	Animal forms
.522	Human forms
.523	Mythological forms

729.53 Grotesques
.541 Conventional forms
.542 Geometrical forms
.543 Fanciful forms.
.55 Mouldings, sculptured
.561 Architraves
.562 Friezes
.563 Cornices
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.597 Mythological
.598 Decorative
.599

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.61 Walls, external
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.616 Metal
.617 Polychromatic
.618 Plastering Stucco
.619
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.625 Tiles
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.628 Plastering Stucco
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.642 Etched
.643 Electroplated
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.651 Metal
.1 Champleve
.2 Cloisonnee
.3 Glaze
.652 Tiles
.1 Glazed
.2 Painted
.3 Printed
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.662 Sgraffito
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.673 Burl work
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See 692.37 for Construction.

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Publications of The Engineering Experiment Station.

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot, 1904.

Circular No. 1. High Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906.

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

Bulletin No. 10. Tests of Plain and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.

Bulletin No. 12. Tests of Reinforced Concrete T-Beams, Series of 1906, by A. N. Talbot. 1907.

Bulletin No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.

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TESTS OF REINFORCED CONCRETE BEAMS SERIES OF 1906.

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CONTENTS.

I. Introduction.

1. *Preliminary.*—The tests on reinforced concrete in the Laboratory of Applied Mechanics of the University of Illinois were continued during the college year of 1905-6. The results on shear and bond were reported in Bulletin No. 8 of the University of Illinois Engineering Experiment Station; those on columns, in Bulletin No. 10; those on T-beams, in Bulletin No. 12. The tests on rectangular beams will be described in this bulletin. The analytical theory of reinforced concrete beams was quite fully treated in Bulletin No. 4, and the methods and nomenclature used in this bulletin will follow those there given.

2. *Scope of Tests.*—The discussion given in Bulletin No. 4 suggested many topics for investigation. Several of these were taken up and considerable information obtained, though it was not feasible to make the investigations complete enough to be fully conclusive. Effect of quality of concrete, effect of method of loading, effect of repetitive loading, and diagonal tension failures were among the topics considered. The beams were of the standard width and depth adopted by the Joint Committee on Concrete and Reinforced Concrete, but in the investigation of resistance to diagonal tension failure the length was varied and shortened to ensure this form of failure. Plain round rods of mild steel were generally used for reinforcement, but a deformed bar was used in some of the beams. The concrete was varied in quality both in the richness of the mixture and in the conditions of fabrication. These tests have since been followed with others bearing on some of the same topics.

3. *Acknowledgment.*—These tests were part of the work of the University of Illinois Engineering Experiment Station. The tests on effect of quality of concrete and effect of method of loading were made in co-operation with the Joint Committee on Concrete and Reinforced Concrete through the sub-committee on tests, of which Mr. Richard L. Humphrey is chairman. The work of testing the beams was done principally as thesis work. The students conducted the tests in a careful and skillful manner, and showed considerable discrimination in making observations and in drawing conclusions. The following members of the class of 1906 in Civil Engineering were connected with the work:

E. W. Sanford, Effect of Quality of Concrete.

H. R. Armeling, Comparison of Methods of Loading.

C. E. Andrew and J. L. Bannon, Effect of Repetition of Load.

T. E. Phipps and R. H. Whipple, A Study of Diagonal Tension Failures.

The work was under the direct supervision of D. A. Abrams, Assistant in the Engineering Experiment Station, and to him and to W. R. Robinson, Assistant in the Engineering Experiment Station, acknowledgment is made for aid in the interpretation of results and in the preparation of this bulletin.

II. Materials, Test Pieces, and Method of Testing.

4. *Materials.*—Materials for the tests on "Effect of Method of Loading" and "Effect of Quality of Concrete" were furnished by the Joint Committee on Concrete and Reinforced Concrete through Mr. Richard L. Humphrey, chairman of the Committee on Tests. Materials for the tests on "Effect of Repetition of Load" and "Diagonal Tension Failure" were furnished by the Engineering Experiment Station. The terms "Joint Committee tests" and "Experiment Station tests" will be used to designate this difference of work and materials.

Stone.— The stone for the Joint Committee tests was a good quality of limestone from Kankakee, Illinois, ordered screened through a 1-in. screen and over a $\frac{1}{4}$-in. screen. It contained from 45% to 50% voids and weighed 85 lb. per cu. ft. loose. The stone for the Experiment Station tests was also a Kankakee limestone somewhat softer than the other, screened as above, and contained 50% to 54% voids. It was somewhat finer than the Joint Committee stone. In the determination of the voids in both stone and sand, the material was poured slowly into the water so that the voids became filled with water and no air was caught.

Sand.—The sand used was the same for all tests. It came from near the Wabash river at Attica, Indiana. It was of good quality, well graded, and fairly clean. It weighed 115 lb. per cu. ft. loose, and contained 28% voids. Table 1 gives the result of a mechanical analysis of this sand.

Cement.—The cement furnished by the Joint Committee was made up of a mixture of five standard American portland cements, selected and mixed by the manufacturers, and was of excellent quality. The cement furnished by the Experiment Station was Chicago AA portland, purchased in the open market of a local

TABLE 1.

MECHANICAL ANALYSIS OF SAND.

Sieve No.	Size of Mesh inches	Per cent passing
4	.208	100
10	.073	73
20	.034	36
50	.011	12
74	.0078	5
100	.0045	2

TABLE 2.

TENSILE STRENGTH OF CHICAGO AA PORTLAND CEMENT.

Ref. No.	Ultimate Strength, lb. per sq. in.			
	Age 7 days		Age 60 days	
	Neat	1–3	Neat	1–3
1	634	283	890	443
2	717	281	916	440
3	732	275	840	422
4	687	217	942	365
5	580	206	872	352
6	731	189	885	....
Av.	680	242	891	404

dealer. The tensile strength of this last cement, as determined from briquettes made by standard methods, is given in Table 2.

Concrete.—Men accustomed to making concrete mixed the materials and made the test beams. Care was taken in measuring, mixing, and tamping, to secure as uniform a concrete as possible. All materials were measured by loose volume. The mixing was done with shovels by hand. The sand and cement were first mixed dry. The stone was then added and the mass mixed until uniform in appearance. Water was added in such proportion as to give a slightly wet concrete.

Steel.—The longitudinal reinforcement consisted generally of $\frac{1}{2}$-in. or $\frac{3}{4}$-in. mild-steel plain round rods. In a few beams $\frac{1}{2}$-in. high-steel Johnson corrugated bars were used. The results of tensile tests of the steel used are given in Table 3. The plain round bars had an average yield point of 40 500 lb. per sq. in. and an ultimate strength of 60 000 lb. per sq. in. The corrugated bars developed an average yield point of 57 300 lb. per sq. in. with an ultimate strength of 87 400 lb. per sq. in. In general, the yield points of the various bars in one beam varied less than 3% from one another.

TABLE 3.

TENSION TESTS OF STEEL USED IN BEAMS.

Values given are in general the average of results of tests of specimens cut from four different rods.

Specimens Taken from Beams No.	Nominal Size inches	Diameter inches	Per cent Elongation in 8 inches	Yield Point lb. per sq. in.	Ultimate Strength lb. per sq. in.
2	$\frac{3}{4}$	.750	31.0	34000	56300
13	$\frac{3}{4}$	.747	33.0	38800	56900
14	$\frac{3}{4}$	.750	29.7	38700	58000
15	$\frac{1}{2}$	.501	29.3	41400	61700
16	$\frac{1}{2}$	.500	28.5	37700	58100
17	$\frac{1}{2}$	.500	28.0	36700	57900
18	$\frac{1}{2}$	.497	29.0	40300	60200
20	$\frac{1}{2}$	.502	28.0	44400	62500
21	$\frac{1}{2}$	.502	31.2	41800	58000
23	$\frac{3}{4}$	.750	31.5	35000	56900
26	$\frac{1}{2}$	.500	29.0	37200	58600
27	$\frac{3}{4}$	.748	31.2	39400	57100
28	$\frac{1}{2}$	.503	29.1	42700	60800
30	$\frac{1}{2}$	.503	29.1	41000	61100
31	$\frac{1}{2}$	.504	28.5	41800	60900
34	$\frac{3}{4}$	.749	32.5	38800	56000
35	$\frac{1}{2}$	.502	29.5	40800	58400
36	$\frac{1}{2}$	.500	28.0	36300	58100
38	$\frac{3}{4}$	.750	29.0	35800	54700
39	$\frac{3}{4}$	.749	32.5	38800	56200
40	$\frac{1}{2}$	.502	28.1	42800	62200
42	$\frac{1}{2}$	.502	29.9	42500	61800
43	$\frac{1}{2}$	.501	28.4	42400	62100
44	$\frac{1}{2}$	.503	28.7	42100	61800
45	$\frac{1}{2}$	.503	29.6	42000	61900
50	$\frac{1}{2}$	.503	29.5	42800	61700

TABLE 3—*Concluded.*

Specimens Taken from Beams No.	Nominal Size inches	Diameter inches	Per cent Elongation in 8 inches	Yield Point lb. per sq. in.	Ultimate Strength lb. per sq. in.
51	½	.502	28.5	41800	60900
52	½	.501	27.9	44200	63100
53	½	.504	29.2	42500	62800
54	½	.505	28.0	42100	61200
55	½	.503	27.8	42000	62300
56	⅝	.622	30.7	37800	60600
58	¾	.753	29.5	40300	62900
59	¾	.753	26.0	41000	65300
60	¾	.750	28.5	39200	63000
61	¾	.752	30.5	39000	59100
62	¾	.750	32.3	40600	58100
63	¾	.748	30.3	42350	62600
64	¾	.748	33.5	37800	54400
65	¾	.747	29.5	41700	61600
68	¾	.754	29.0	44200	61900
69	¾	.747	29.5	42200	62700
70	¾	.752	29.5	44500	60700
71	¾	.749	32.2	40100	59200
72	¾	.748	31.5	39900	58900
73	¾	.750	31.2	40700	56900
74	½	.499	27.6	43900	60100
66*	½ in. (net section = 0.25 sq. in.)		16.1	58800	91100
67*			17.4	57300	87300

* Corrugated bars.

5. *Test Beams.*—In all of the tests herein discussed the cross-section of the beams was 8 in. x 11 in., the center of the steel being placed 10 in. below the top surface except in some cases where the ends of the bars were bent up. In the tests on "Diagonal Tension Failure" the test span varied from 6 ft. to 12 ft. In all the other series of tests a 12-ft. span was used. Unless otherwise specified the reinforcing bars were straight and were placed horizontally throughout the beam. In the beams marked "Bars bent up" the bars were bent up at a point about 3 in. outside the load points and passed diagonally either in a straight line or in a slightly curved line to a point within 2 in. or 3 in. of the top of the beam near its ends. In several beams stirrups of ½-in. plain

round bars were used. These stirrups were placed 12 in. apart longitudinally throughout the outer thirds of the span length, beginning at the load points. They were U-shaped and passed under all the reinforcing bars and extended nearly to the top of the beam. The stirrups were left very close to the sides of the beam. For general data on all beams see Table 5.

TABLE 4.

COMPRESSION TESTS OF CUBES AND CYLINDERS.

Concrete as in Beam No.	Kind of Concrete	Compressive Strength lb. per sq. in.	
		Cubes	Cylinders
59	1-2-4	2030	1700
61	1-2-4	3500	....
69	1-2-4	1510	....
Av.	....	2350	1700
51	1-3-5½	....	1470
58	1-3-5½	1580	1060
60	1-3-5½	1690	1060
65	1-3-5½	2360	....
68	1-3-5½	1850	885
70*	1-3-5½	2250	1100
72	1-3-5½	1770	540
73*	1-3-5½	....	770
Av.	....	1920	980
5†	1-3-6	1390	
6†	1-3-6	1420	
7†	1-3-6	1050	
12†	1-3-6	1080	
14	1-3-6	1600	
18	1-3-6	1380	
19	1-3-6	1170	
Av.	....	1300	
71	1-5-10	1230	

* Poorly mixed.
† Poorly made.

TABLE 5.

GENERAL DATA ON BEAMS.

Beam No.	Kind of Concrete	Reinforcement		Span, ft.	Age at Test days	Classification	
		Per cent	Amount and Disposition			Table No.	Kind
3	1-3-6	0.98	4 ½-in. round.	12	72	10	E. S.
4	1-3-6	0.98	4 ½-in. round.	12	74	12	E. S.
5	1-3-6	0.98	4 ½-in. round.	12	71	10	E. S.
6	1-3-6	0.98	4 ½-in. round.	10	71	10	E. S.
7	1-3-6	0.98	4 ½-in. round. Bars bent up.	10	71	11	E. S.
8	1-3-6	2.21	4 ¾-in. round.	10	76	10	E. S.
9	1-3-6	2.21	4 ¾-in. round.	10	76	10	E. S.
10	1-3-6	0.98	4 ½-in. round.	12	73	12	E. S.
11	1-3-5½	0.98	4 ½-in. round.	12	73	10	E. S.
12	1-3-6	2.21	4 ¾-in. round.	10	70	12	E. S.
13	1-3-6	2.21	4 ¾-in. round. Bars curved up.	10	69	11	E. S.
14	1-3-6	2.21	4 ¾-in. round. Bars curved up.	10	68	11	E. S.
15	1-3-6	0.98	4 ½-in. round.	8	69	10	E. S.
16	1-3-6	0.98	4 ½-in. round.	8	69	10	E. S.
17	1-3-6	0.98	4 ½-in. round. Bars bent up.	8	70	11	E. S.
18	1-3-6	0.98	4 ½-in. round.	6	71	10	E. S.
19	1-3-6	0.98	4 ½-in. round.	6	67	10	E. S.
20	1-3-6	0.98	4 ½-in. round. Bars bent up.	6	67	11	E. S.
21	1-3-6	0.98	4 ½-in. round. Bars bent up.	6	68	11	E. S.
22	1-3-6	0.98	4 ½-in. round. 2 bars bent up.	6	70	11	E. S.
23	1-3-5½	2.21	4 ¾-in. round.	10	67	10	E. S.
25	1-3-5½	0.98	4 ½-in. round.	6	70	10	E. S.
26	1-3-5½	0.98	4 ½-in. round. Bars curved up.	8	68	12	E. S.
27	1-3-5½	2.21	4 ¾-in. round.	8	68	10	E. S.
28	1-2-4	0.98	4 ½-in. round.	12	70	8, 9, 12	E. S.
29	1-3-5½	0.98	4 ½-in. round.	12	70	8, 9, 10	E. S.
30	1-4-7½	0.98	4 ½-in. round.	12	71	8, 9, 10	E. S.
31	1-2-4	0.98	4 ½-in. round.	12	78	8, 9, 12	E. S.
32	1-3-5½	0.98	4 ½-in. round.	12	79	8, 9, 12	E. S.
33	1-3-5½	0.98	4 ½-in. round.	6	73	10	E. S.
34	1-3-5½	2.21	4 ¾-in. round.	8	67	10	E. S.
35	1-4-7½	0.98	4 ½-in. round.	12	75	8, 9, 12	E. S.
36	1-3-5½	0.98	4 ½-in. round. Bars bent up.	10	61	11	E. S.
37	1-3-5½	2.21	4 ¾-in. round.	8	70	10	E. S.
38	1-3-5½	2.21	4 ¾-in. round. Bars bent up.	8	64	11	E. S.
39	1-3-5½	2.21	4 ¾-in. round. Bars bent up.	8	64	11	E. S.
40	1-3-5½	0.98	4 ½-in. round.	12	62	7	J. C.
42	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
43	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
44	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
45	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
46	1-3-5½	0.98	4 ½-in. round.	6	85	10	E. S.
47	1-2-4	0.98	4 ½-in. round.	6	88	10	E. S.
48	1-2-4	0.98	4 ½-in. round.	6	84	10	E. S.
49	1-3-5½	0.98	4 ½-in. round.	6	82	10	E. S.
50	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
51	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.

TABLE 5.—*Concluded*

GENERAL DATA ON BEAMS.

Beam No.	Kind of Concrete	Reinforcement		Span, ft.	Age at Test days	Classification	
		Per cent	Amount and Disposition			Table No.	Kind
52	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
53	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
54	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
55	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
56	1-3-5½	0.98	4 ½-in. round.	12	60	7	J. C.
57	1-2-4	1.15	3 ⅝-in. round.	12	76	6	J. C.
58	1-3-5½	1.10	2 ¾-in. round.	12	61	6	J. C.
59	1-2-4	1.10	2 ¾-in. round.	12	62	6	J. C.
60	1-3-5½	1.10	2 ¾-in. round.	12	61	6	J. C.
61	1-2-4	1.10	2 ¾-in. round.	12	61	6	J. C.
62	1-5-10	1.10	2 ¾-in. round.	12	62	6, 10	J. C.
63	1-5-10	1.10	2 ¾-in. round.	12	61	6, 10	J. C.
64	1-3-5½	1.10	2 ¾-in. round.	12	61	6	J. C.
65	1-3-5½	1.10	2 ¾-in. round.	12	60	6	J. C.
66	1-5-10	1.25	4 ½-in. corrugated bars.	12	59	6, 10	J. C.
67	1-5-10	1.25	4 ½-in. corrugated bars.	12	60	6, 10	J. C.
68	1-3-5½	1.65	3 ¾-in. round. 10 ½-in. stirrups.	12	60	6, 10	J. C.
69	1-2-4	1.65	3 ¾-in. round. 10 ½-in. stirrups.	12	61	6	J. C.
70	1-3-5½	1.65	3 ¾-in. round. 10 ½-in. stirrups.	12	60	6	J. C.
71	1-5-10	1.65	3 ¾-in. round. 10 ½-in. stirrups.	12	60	6, 10	J. C.
72	1-3-5½	1.10	2 ¾-in. round. 10 ½-in. stirrups.	12	60	6	J. C.
73	1-3-5½	1.10	2 ¾-in. round. 10 ½-in. stirrups.	12	60	6	J. C.
74	1-3-5½	0.98	4 ½-in. round.	10	62	12	E. S.

NOTE:—E. S. and J. C. refer to Engineering Experiment Station and Joint Committee respectively. For explanation of terms, see "4. Materials," p. 3.

6. *Making of the Beams.*—The beams were made directly on the concrete floor of the laboratory, a strip of building paper being laid beneath the forms. Several proportions of concrete were used, varying from 1-2-4 to 1-5-10 by loose volume. A number of the first beams were made of 1-3-6 mixture, and the later ones of 1-3-5½, as it was thought that the voids in the stone were not properly filled in the 1-3-6 mixture. The forms, which were of the ordinary wooden knock-down type, were removed four days after making the beams and the beams were not moved in any way for 14 days. Generally the stone for the concrete was dampened and the concrete well mixed and wet enough to secure proper hardening. The making of the beams

was skillfully done. In Beams No. 3 to 13 inclusive, however, through some oversight the stone (a porous material), was not dampened, insufficient water was used in mixing, the making and

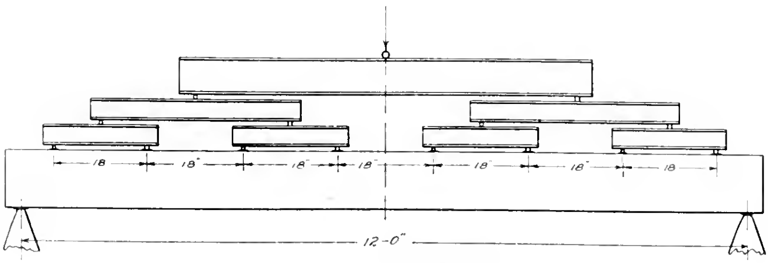


FIG. 1. 8-POINT LOADING.

tamping were not properly done, and the concrete was allowed to become too dry. The beams so made proved to be of inferior concrete and are referred to as poorly made concrete. The low results obtained are of interest in showing the effect of improper methods even if enough cement is used.

7. *Minor Test Pieces.*—Tests were made on 6-in. cubes and on 8-in. cylinders 16 in. high taken from concrete used in some of the beams. The results of these tests are given in Table 4. The values given for the cubes are the averages of three test specimens. For the cylinders, a single test specimen was used.

8. *Storage.*—The beams were stored in a room the temperature of which was from 60° F. to 70° F. They were tested at the age of about 60 days.

9. *Method of Testing.*—The usual method of testing was by loads applied at the one-third points as described in Bulletin No. 4, page 34. The beams were all tested in the 200 000-lb. Olsen testing machine, and in all cases except the tests on "Effect of Method of Loading," were loaded at the one-third points. The method used for loading at eight points is shown in Fig. 1. The supports of the beam allowed longitudinal movement, the bottom of the rocker being an arc of 12-in. radius, and the top, on which cast-iron blocks rested, having a radius of 1½ in. Turned steel rollers, 2 in. in diameter, were used for applying the load at the third points. The blocks at the supports and load points were bedded in plaster of paris which was allowed to harden under the weight of the beam and the apparatus used in loading before the

load was applied. The cubes, cylinders, and steel were tested in the 100 000-lb. Riehlé and 200 000-lb. Olsen testing machines.

Center deflections were read on all the beams. Deformations of the upper fiber and steel were measured by means of four extensometers. The methods of measuring deflections and deformations were fully described in Bulletin No. 4.

TABLE 6.

EFFECT OF QUALITY OF CONCRETE.

Span 12 ft. Loaded at one-third points.

Beam No.	Maximum Load, lb.	k	Per cent Reinforcement	Stress in Steel lb. per sq. in.	Vertical Shearing Stress $v = \frac{V}{bd'}$ lb. per sq. in.	Manner of Failure
			1-2-4 Concrete.			
57	11730	.43	1.15	39800	96	Tension.
59	12000	.53	1.10	44000	97	Tension.
61	10960	.47	1.10	39700	90	Tension.
69*	16000	.57	1.65	39000	129	Tension.
			1-3-5½ Concrete.			
58	9860	.52	1.10	36900	82	Tension.
60	10360	.57	1.10	39400	85	Tension.
64	9850	.55	1.10	37300	82	Tension.
65	10000	.54	1.10	37600	83	Tension.
68*	14220	.57	1.65	35000	115	Diagonal Tension.
70*	13710	.69	1.65	35800	112	Compression (Poor concrete)
72*	10270	.47	1.10	37400	85	Tension.
73*	9900	.52	1.10	37000	82	Tension.
			1-5-10 Concrete.			
62	8850	.60	1.10	34600	74	Diagonal Tension.
63	7360	.48	1.10	28100	63	Diagonal Tension.
66†	8000	.63	1.25	29400	69	Diagonal Tension.
67†	7850	.57	1.25	27100	68	Diagonal Tension.
71*	7600	.59	1.65	20200	67	Diagonal Tension.

* Stirrups.

† Reinforced with corrugated bars.

III. Experimental Data and Discussion.

10. *Explanation of Tables 6 to 12.*—In Tables 6 to 12, the position of the neutral axis was obtained by the method used in Bulletin No. 4. In calculating the per cent of reinforcement the area of the beam above the center of the reinforcing bars is used. The columns headed "Maximum Applied Load" do not include the weight of the beam loading apparatus, but these weights were considered in calculating the stress in the steel. In determining the amount of the vertical shear, the weight of the beam and loading apparatus was considered, 6 lb. per sq. in. being added to the unit-stress for a 6-ft. beam, 7 for an 8-ft. beam, 8 for a 10-ft. beam, and 10 for a 12-ft. beam. In obtaining the vertical shear, the formula $v = \frac{V}{.86bd}$ or $.0145V$ was used for 1% beams and $v = \frac{V}{.81bd}$ or $.0154V$ for 2.2% beams.

11. *Effect of Quality of Concrete.*—In this series, tests were made on beams made of three kinds or grades of concrete,—1-2-4, 1-3-5½, and 1-5-10 mixtures. The purpose of this series was to determine the effect of quality of concrete upon the strength of the beam and upon the manner of failure. The beams were planned to give a variety of manners of failure,—tension in the steel, compression in the concrete, and diagonal tension in the concrete. Table 6 gives the results of this series. The calculations were made as described under "10. Explanation of Tables". No attempt is made to calculate the diagonal tensile stresses developed, but the ability to resist diagonal tension will be compared by means of the vertical shearing stresses developed. The load was applied at the one-third points of the beams. From the tables it will be noted that the manner of failure for beams of these proportions depends upon the richness of the concrete. Counting the effect of the weight of the beam and loading apparatus, it is seen that all the beams made with 1-2-4 concrete failed by tension in the steel at calculated stresses somewhat above the elastic limit of the steel. Beam No. 57, (Fig. 4), is typical of the appearance of the beams after failure. Beam No. 69, having 1.65% reinforcement, has a load-compression diagram (Fig.12) which indicates that the stress in the concrete at the maximum load was well within the limits of its ultimate compressive strength. The vertical shearing stress developed in this

beam was 124 lb. per sq. in. and there was no indication of approaching failure by diagonal tension.

Of the test beams of 1-3-5½ concrete all but two failed by tension in the steel. The calculated stresses in the steel, when allowance is made for the weight of the beam, are slightly above the elastic limit of the steel. The two not failing by tension in the steel, when compared by the stresses computed either from the bending moment or the observed deformations, gave stresses in the steel not much lower than the average of the remainder of the series. Both of these beams, therefore, had hardly reached the load which would have been followed by failure by tension in the steel. Beam No. 68 failed by diagonal tension at a calculated vertical shearing stress of 115 lb. per sq. in. No. 70 failed by compression of the concrete. The compression diagram (Fig. 13) shows that the concrete in this beam lacked stiffness, the amount of deformation being more than for the average beam but not much more than that of No. 68, its companion beam, as is seen from the load-deformation diagrams. And yet this beam of 1-3-5½ concrete and 1.65% reinforcement carried a load nearly to the elastic limit of the steel reinforcement.

All the beams made with 1-5-10 concrete failed by diagonal tension at loads which show a rather narrow range regardless of the amount or method of reinforcement. The vertical shearing unit-stress developed averaged 68 lb. per sq. in. As the beams failed by diagonal tension at loads much smaller than those at which failure by compression in the concrete may be expected, there is nothing in these tests upon which to base the limit of the concrete or the amount of reinforcement at which the compressive strength of the concrete and the tensile strength of the steel may be considered to be balanced.

A comparison of beams having 1.1% reinforcement which failed by tension in the steel shows that the 1-2-4 beams carried greater loads than the 1-3-5½ beams, the additional load amounting to 10% or 15%. This increase of load probably is due to the fact that the greater strength of the richer concrete allows the steel to be stretched a greater distance beyond the elastic limit before developing the full compressive strength of the concrete and also that the moment arm of the couple formed by the compressive stresses is somewhat greater with the richer concrete. The added strength of the richer concrete in preventing failure by

diagonal tension is apparent. This feature of the series will be further discussed under "14. Diagonal Tension Failures". As will be shown afterward, the arrangement of stirrups used was not well planned and their presence seemed not to add to the strength of the beams, although in Beams No. 68 and 71 it might have been expected that well designed stirrups would prevent failure by diagonal tension.

12. *Effect of Method of Loading.*—It was the purpose of this series to determine the effect of the method of loading upon the resisting moment developed in the beam. With this in view, the beams were so proportioned that failure by tension in the steel was expected in all cases. In Bulletin No. 4, page 54, a discussion of this topic is given. It was there stated that beams loaded at the middle have been found to develop a higher moment of resistance than is to be expected if the distribution of stresses is as assumed in the ordinary theory of flexure. Six methods of loading were used in the tests of this series: (1) load applied at center of the span only; (2) load applied at two points 1½ feet apart; (3) load applied at two points 3 feet apart; (4) load applied at the one-third points; (5) load applied at two points 7½ feet apart; (6) load applied at eight points (to approximate a uniform load). The appliances used for the loading at eight points have been described under "9. Method of Testing".

Table 7 gives the results of these tests, together with the calculated stresses in the steel. All beams failed by tension in the steel, as was clearly shown by the load-deformation diagrams. If the effect of the weight of the beam and loading apparatus is included, it will be seen that the calculated stresses in the steel all lie above the elastic limit. A comparison of the resisting moments of the beams may be made by comparing the calculated stresses in the steel, given in Table 7, since the tests of the steel used in these beams show that there was little variation in the yield point of the test pieces. It will be noted that the highest stress developed was in beams having the loading at the middle, and that when the two loads were close to the middle the results were not much lower. For the other methods of loading the variation in stress developed was not large, no greater than may be expected with the difference in the materials and fabrication in such beams, though the method in which the load was applied at eight points gave a somewhat higher resisting moment. These

TABLE 7.

EFFECT OF METHOD OF LOADING

Reinforcement .98%. Concrete 1-3-5½. Span 12 ft. All failed by tension in the steel.

Beam No.	Method of Loading	Maximum Applied Load lb.	k	Stress in Steel lb. per sq. in.
50	Center.	7400	.45	45200
52	Center.	7650	.38	45400
53	2 points 1½ ft. apart.	7900	.45	42500
54	2 points 1½ ft. apart.	8250	.42	43500
55	2 points 3 ft. apart.	8900	.44	40700
56	2 points 3 ft. apart.	9610	.51	45000
40	One-third points.	10000	.46	41000
42	One-third points.	9420	.47	39000
45	2 points 7½ ft. apart.	17300	.50	40100
51	2 points 7½ ft. apart.	18000	.45	40700
43	8 points 18 in. apart.	14000	.44	42100
44	8 points 18 in. apart.	15000	.41	44300

tests go to show the general applicability of the ordinary beam theory to simple beams without end restraint or horizontal restraint for any of the usual methods of loading, with the exception of center loading, provided, of course, that the proportions of the beam are such that the method of failure is by tension in the steel. It will be seen that the beams loaded at the middle give about 10% greater resistance than the more usual methods of loading. This excess is not so great as has been found in beams having a high percentage of reinforcement. With high reinforcement the resulting moment developed is considerably greater than for loading at the one-third points. Evidently under such conditions loading at the middle gives a distribution of stresses at sections near the center of the beam which is different from that assumed in the ordinary theory of flexure.

The load-deformation curves have the same general characteristics in all of the beams. The position of the neutral axis, as determined by the method used, is nearly the same for the several methods of loading, the variation being as little as may be ex-

pected in tests of this character and no characteristic difference being noticeable in any method of loading. Of course, with the load applied in the middle the deformations were taken over so great a gauged length that a discrepancy in the distribution of stress at a section at the middle had little effect on the values found.

13. *Effect of Repetitive Loading.*—Tests were made on six beams to determine the effect of repeatedly applying and releasing the load on the beam, from 24 to 30 applications of a single load being made. Three mixtures of concrete were used, thus permitting a study of the effect of quality of concrete. All beams were reinforced with 1% of steel. The load applied was 5000 lb.

TABLE 8.

EFFECT OF REPETITIVE LOADING.

Span 12 ft. Loaded at one-third points.

Beam No.	Mixture	Age days	Per cent Reinforcement	Repeated Load lb.	No. of Applications	Failed at lb.	Manner of Failure
28	1-2-4	70	0.98	6000	26	9900	Tension.
31	1-2-4	78	0.98	6000	25	9400	Tension.
29	1-3-5½	71	0.98	5000	30	10000	Diagonal tension.
32	1-3-5½	79	0.98	6000	24	9800	Tension.
30	1-4-7½	71	0.98	5000	30	5900	Diagonal tension.
35	1-4-7½	75	0.98	5000	30	7500	Compression.

TABLE 9.

DEFLECTIONS UNDER REPETITIVE LOADING.

Beam No.	Mixture	Center Deflection in inches for 5000-lb. Load.						
		Application						
		1st	5th	10th	15th	20th	25th	30th
28	1-2-4	0.25	0.33	0.34	0.36	0.37	0.38	
31	1-2-4	0.25	0.33	0.35	0.35	0.36	0.37	
29	1-3-5½	0.15	0.25	0.25	0.25	0.25	0.26	0.25
32	1-3-5½	0.24	0.31	0.33	0.34	0.34		
30	1-4-7½	0.40	0.49	0.54	0.57	0.60	0.62	0.65
35	1-4-7½	0.31	0.38	0.40	0.41	0.41	0.41	0.42

in three beams, and 6000 lb. in the other three. These loads were from 50 % to 85 % of the maximum load carried by the beam when the load was finally increased to the point of failure. The deflection at the midpoint of the span was measured, as were the deformations at the top and bottom for a gauged length along the middle of the beam, though the latter measurements were not entirely satisfactory. Table 8 and Table 9 give results of these tests.

The following notes show the principal features of the tests of the several beams.

Beam No. 28. The beam was made of 1-2-4 concrete. The general behavior of this beam during the repetition of the 6000-lb. load is representative of the action of the other beams. Hair cracks appeared on the tension side of the beam in the middle third of the length, one or more of them usually on the first application of the load and others at subsequent applications, as shown in Fig. 2. In this beam hair cracks appeared at the third, eighth, thirteenth, and twenty-sixth applications. In each case the cracks closed upon the removal of the load. Upon increasing the load after the twenty-sixth application of 6000 lb., the cracks opened still further. Finally the crack marked 8 opened much more rapidly, the beam failed by tension in the steel, and this was followed by the load dropping off and the concrete finally crushing at the top at a load much less than the maximum. It may be noted that the deflection of the beam increased with the repetition of the 6000-lb. load, the amount at the twenty-fifth application being 50% more than at the first. The position of the cracks is shown in Fig. 2, the numbers indicating the applications at which the cracks were noted.

Beam No. 31. The beam was of 1-2-4 concrete. Hair cracks appeared at the second, fifth, seventh, tenth, and twenty-fifth applications of the load of 6000 lb. On increasing the load after the twenty-fifth application, the cracks opened, and at 8000 lb. crack No. 2 (Fig. 2) rapidly widened. At a load of 9400 lb., the steel passed its yield point and as usual this was finally followed with the crushing of concrete at the top of the beam. The increase in the deflection of the beam at the twenty-fifth application over that at the initial application of the load was 50%. It should be noted that the diagonal crack marked 10 formed at the 10th application of the load, but, although it widened when the load was increased beyond 6000 lb., it did not cause failure. The vertical shearing

unit-stress, as calculated by equation 18 (See page 20, Bulletin No. 4), was 53 lb. per sq. in. for a load of 6000 lb., and 78 lb. per sq. in. at failure.

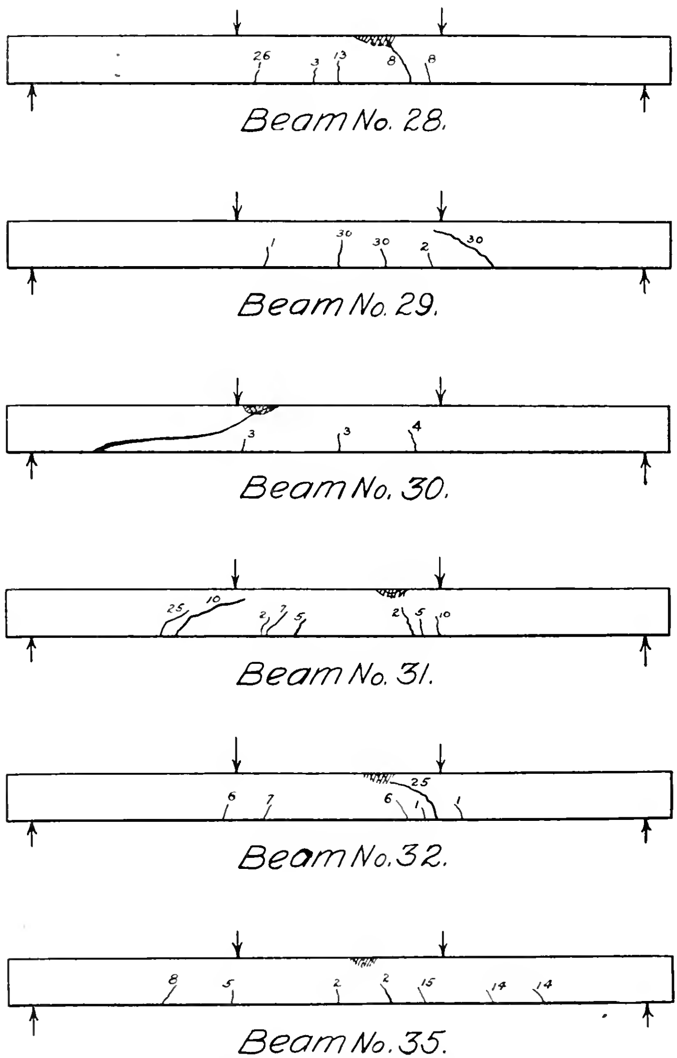


FIG. 2. SKETCHES SHOWING BEAMS AFTER FAILURE UNDER REPETITIVE LOADING.

Beam No. 29. The beam was made of 1-3-5½ concrete. A load of 5000 lb. was applied 30 times. Hair cracks appeared as shown in the sketch in Fig. 2. The deflection for the load of 5000 lb. increased 67% during the repetitions. At a load of 9000 lb. a diagonal crack appeared one foot outside the load point, and the beam finally failed by diagonal tension along this crack. The vertical shearing unit-stress at this load was 76 lb. per sq. in., and at the maximum load 83 lb. per sq. in.

Beam No. 32. The beam was made of 1-3-5½ concrete. A load of 6000 lb. was applied 24 times. Two hair cracks appeared at the first application, and several more at later applications of the load, but no additional effect was observed. As the load was finally increased to an amount near 9400 lb., a crack near the load point appeared, and failure by tension in the steel at this point followed at a maximum load of 9800 lb. The repetition of the load gave a greatly increased deformation in the upper fiber (See Fig. 14) but when the load was increased beyond 6000 lb., the upward direction of the deformation curve for the upper fiber indicates that the concrete had not lost its strength or elasticity. The changes in the deflection are shown in Fig. 10.

Beam No. 30. The beam was made of 1-4-7½ concrete. A load of 5000 lb. was applied 30 times. Hair cracks appeared on the third and fourth applications. On increasing the load a diagonal crack appeared outside the load point, and the beam failed by diagonal tension at a maximum load of 5900 lb., followed by a stripping of the bars for some distance beyond. The vertical shearing unit-stress for this load was 53 lb. per sq. in. The exposed ends of the bars showed a slip in the concrete after the maximum load was reached. Fig. 8 gives the changes in deflection.

Beam No. 35. The beam was made of 1-4-7½ concrete. Thirty applications of the load of 5000 lb. were made. Fine hair cracks appeared at the bottom over the the middle third during the repetition, and a few outside of the load points. The beam finally failed by compression in the upper face of the beam at a load of 7500 lb. It seems possible that the strength of the concrete may have been affected by the repetition of stress, although it is more likely that the test is an example of the effect of poor concrete.

These tests throw light upon the phenomena of repetitive loading and show the need of further investigation in this direction, but they are not at all conclusive. The manner of failure in general is the same as may be expected with beams of the same reinforcement and same quality of concrete loaded progressively to final failure. Whether the maximum load carried in the case of the repetitive loading is less than would have been the case with progressive loading is not known. There are some indications that the maximum load was less than it would have been without repetition.

The increase in the deflection of the beams with repetition of the load is quite apparent. Much of this increase is due to the increased amount of shortening of the concrete in the compression side of the beam with repetition. A part is due to the breaking of the concrete in tension and the transferring of the tensile stress once taken by the concrete to the steel itself. This accounts for part of the set in the deflection curve upon the release of the load. Part of the set must be due to the concrete in the lower fiber not meshing, so to speak, when the load is released after numerous fine cracks have appeared. For this reason some tension remains in the steel reinforcement after the load is taken off. It seems evident that upon the removal of the load the beam does not regain its original shape and a section which was plane before bending will not be plane upon release of the load. The plastic nature of the concrete on the compression side gives a set, and the concrete on the tension side is unable to return to its original position; the two act together to cause the fibers not to return to the original plane section. These several causes operate together to produce the permanent deflection or set.

The load applied in the cases of the leaner concretes was 67% to 85% of the maximum load which the beam finally held. In the case of the better concrete, the repeated load was 50% to 60% of the maximum load. The effect of the quality of the concrete is seen in the manner of failure.

This topic is one of such importance that it merits fuller investigation. The few tests which have been made indicate that the deflection and the deformations increase with repetition. It seems quite probable that the breaking load under a number of repetitions will be smaller than under a single load. It seems to be true also that the amount of reinforcement for which the elas-

tic tensile strength of the steel used for reinforcement may be considered to balance the compressive strength in the concrete of the beam (which the writer calls "the balanced reinforcement") should be taken at a lower percentage in beams subjected to a repetition of load than is found necessary in the case of beams tested by means of a gradually applied load.

The term "balanced reinforcement" referred to above is a convenient term for general use. It should be taken to mean that amount of reinforcement for which the allowable stress in the steel and the allowable stress in the concrete both exist at the same time. The factors of safety for the two materials will not be the same. The determination of the balanced reinforcement for given conditions of materials, fabrication, and use is a matter involving calculation and experimentation, but in any event the judgment of the designer must enter into the choice of the amount.

14. *Diagonal Tension Failures.*—As shown in Bulletin No. 4 (pages 20, 21, and 26), certain secondary stresses or web stresses exist in the concrete of a reinforced concrete beam in addition to the horizontal or longitudinal tensile and compressive stresses which are always considered in the analysis. Strictly speaking, the shearing stresses developed under ordinary conditions are relatively light, and the actual shearing strength of concrete is considerably greater than the shearing stress which exists in ordinary beams at the time of failure. It is quite common, however, to use the term "shearing failure" as a name for a class of failures in the web of a beam, but it must not be understood from this use of terms that the failure necessarily involves actual failure by shear. Generally speaking, such failures are due to the inability of the concrete to resist the tensile stresses developed in the web in a diagonal direction, and the term "diagonal tension failure" is a much more appropriate name for this form of failure. It is a principle of mechanics that where shearing stresses exist tensile and compressive stresses are set up at an angle with the direction of the shearing stresses. If longitudinal tensile stress also exists in the concrete, the diagonal tensile stress induced by the combination of these with the shear is even higher than that due to shear alone. If v represents the horizontal and vertical unit-stress at any point in the web of a beam and s the horizontal tensile unit-stress existing in the concrete at the same

point, then, as shown in Bulletin No. 4, the formula for the maximum diagonal tensile unit-stress is

$$t = \tfrac{1}{2} s + \sqrt{\tfrac{1}{4} s^2 + v^2} \quad \ldots\ldots\ldots\ldots (19)$$

If there is no longitudinal tension in the concrete, this formula reduces to

$$t = v \quad \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

and maximum diagonal tension makes an angle of 45° with the horizontal and is equal in intensity to the vertical shearing stress.

It is evident then that the amount of this diagonal tension is dependent upon both the shearing stress and the longitudinal tensile stress in the concrete at the point considered. The amount of longitudinal tension is not easy to determine and hence the actual amount of the diagonal tensile stress is uncertain. The best method for ordinary computation seems to be to compute the vertical shearing unit-stress and make all calculations upon the basis of this value. The value of the vertical shearing unit-stress, where the longitudinal reinforcement is straight (not bent up or inclined), may be computed from the formula given in Bulletin No. 4,

$$v = \frac{V}{bd'} \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

where V is the total external vertical shear at the section considered, b is the breadth of the beam, d' is the distance from the center of the steel to the center of the compressive stresses. For beams with 1% reinforcement d' is about 0.86 d, d being the distance from the center of the steel to the upper face of the beam.

The value of v thus calculated for beams which fail by diagonal tension ranges from one-half to one-third of the tensile strength of the concrete. Diagonal tension failures are frequently characterized by sudden failures without much warning, as is the case in the failure of plain concrete beams. A variation from this gives a slower failure, part of the shear being carried through the reinforcing bars, and the ultimate failure involving the splitting and stripping of the bars from the beam above. When the reinforcing bars are bent up or inclined toward the ends of the beams the distribution of the vertical shear is different from that just outlined and the analysis is more complex. However, for purposes of comparison, the use of equation (18) is advantageous, and the values of v given in the tables for beams

with bars inclined are calculated by this formula, using d as 10 in., though the amounts as calculated do not represent the actual vertical shear.

Forty test beams were made with a view of studying diagonal tension failure. To make a sufficient variety of conditions the concrete was varied from a fairly rich mixture to a very lean concrete. The first of the 1-3-6 concrete beams numbered up to 13 were very poorly made, as described under "6. Making of the Beams", and the general appearance of the concrete and its action during the tests go to show that the concrete was of a very inferior quality. The beams were made with the same depth, and their length was varied to give a variable relation between depth and span.

Table 10 gives the results of beams having the reinforcing bars horizontal and in which failure occurred by diagonal tension. The beams are grouped according to the quality of the concrete.

TABLE 10.

DIAGONAL TENSION FAILURES.

BARS HORIZONTAL.

All beams loaded at one-third points.

Beam No.	Span ft.	Per cent Reinforcement	k	Maximum Applied Load lb.	Vertical Shearing Stress lb. per sq. in. $v = \frac{V}{bd'}$	Manner of Failure
			1-5-10 Concrete.			
62	12	1.10	.60	8850	74	Diagonal tension.
63	12	1.10	.48	7360	63	Diagonal tension.
66	12	1.25	.71	8000	69	Diagonal tension.
67	12	1.25	.57	7850	68	Diagonal tension.
71	12	1.65	.59	7600	67	Diagonal tension.
Av.	......	....	....	....	68	
			1-4-7½ Concrete.			
30	12	0.98	.71	5900	53	Diagonal tension.

TABLE 10—*Concluded*

Beam No.	Span ft.	Per cent Reinforcement	k	Maximum Applied Load lb.	Vertical Shearing Stress lb. per sq. in. $v = \frac{V}{bd'}$	Manner of Failure
			1-3-6 Concrete.			
3	12	0.98	.48	7380	64	Diagonal tension.
5	12	0.98	.44	6200	55	Diagonal tension.
6	10	0.98	.47	7050	59	Diagonal tension.
8	10	2.21	.56	8470	73	Diagonal tension.
9	10	2.21	.64	9150	79	Diagonal tension.
15	8	0.98	.52	13000	107	Diagonal tension.
16	8	0.98	.41	12420	97	Diagonal tension.
18	6	0.98	.40	13000	101	Diagonal tension.
19	6	0.98	.54	12760	99	Diagonal tension.
Av.	......	....	.....	....	81	
			1-3-5½ Concrete.			
11	12	0.98	.52	10000	83	Diagonal tension.
29	12	0.98	.55	10000	83	Diagonal tension.
68	12	1.65	.57	14220	115	Diagonal tension.
23	10	2.21	.61	13830	115	Diagonal tension.
27	8	2.21	.67	11000	92	Diagonal tension.
34	8	2.21	.76	11230	94	Diagonal tension.
37	8	2.21	.70	15140	114	Diagonal tension.
25	6	0.98	.56	15430	118	Diagonal tension.
33	6	0.98	.57	15670	120	Diagonal tension.
46	6	0.98	.34	13700	106	Diagonal tension.
49	6	0.98	.49	19000	144	Diagonal tension.
Av.	......	.....	.....	....	108	
			1-2-4 Concrete.			
47	6	0.98	.46	18800	142	Diagonal tension.
48	6	0.98	.38	17940	136	Diagonal tension.
Av.	......	.....	......	....	139	

The value of v, calculated by equation (18), offers a means of comparison of the resistance of the concrete to failure by diagonal tension. The effect of lean concrete and of poorly made concrete is quite evident. The results are instructive. The low values

for the poor concrete may be helpful as a warning against assuming high web stresses for beams in which the concrete may not be well made.

The range of the values of the vertical shearing unit-stress v found in these tests with beams having the reinforcing rods in a horizontal position may be summarized as follows, the results being obtained with a single application of the load on beams about 60 days old:

1-2-4 concrete	136 to 142 lb. per sq. in.	Av. 139 lb. per sq. in.
1-3-6 concrete	92 to 115 lb. per sq. in.	Av. 99 lb. per sq. in.
1-3-6 poorly made concrete	55 to 83 lb. per sq. in.	Av. 69 lb. per sq. in.
1-5-10 concrete	63 to 74 lb. per sq. in.	Av. 68 lb. per sq. in.

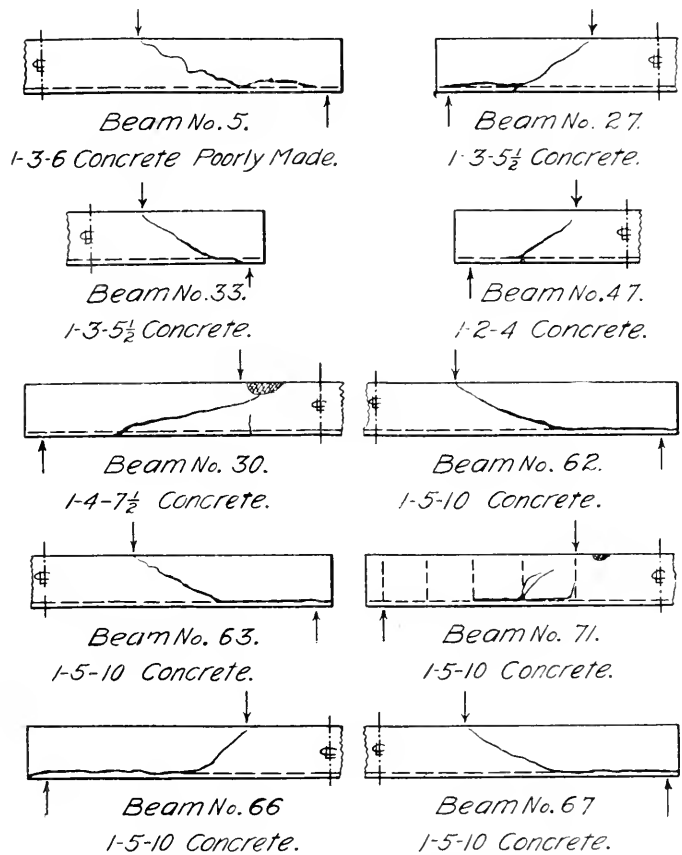


FIG. 3. SKETCHES SHOWING BEAMS AFTER FAILURE.

The one beam of 1-4-7½ concrete which failed in this way gave 43 lb. per sq. in. This beam was subjected to repetitive loading. These results show the importance of using a rich concrete in the web of reinforced concrete beams which are subjected to any considerable amount of diagonal tension when there is no metallic web reinforcement or when the web reinforcement is not effective. It is probable that not enough attention has been given to this element in the design of short and deep beams.

Fig. 3 gives sketches showing the cracks which were observed in these beams. The sketches represent the position of the cracks after the failure of the beam, or after the load had reached a maximum, and do not indicate the position or extent of the cracks within the maximum load. Fig. 4 and 5 are reproduced from photographs and give the appearance of beams after failure. Generally speaking, the crack when first observed, extended from the bottom of the beam to the steel reinforcement and from the steel reinforcement diagonally a short distance toward a load point, although in some cases the diagonal crack was observed before the vertical crack was visible. Sometimes this diagonal crack was observed before the maximum load was reached and sometimes not until the maximum load had been passed, or even until after the beam had failed quite suddenly. In some of the beams the diagonal crack was seen to extend forward slowly toward the load point before or just after the maximum load was reached and then a horizontal crack grew along the level of the top of the reinforcing bars toward the support. The phenomena of final failure were frequently connected with the slipping of the reinforcing bars or with the stripping of these bars from the concrete above as was described in Bulletin No. 4 for a former series of tests. The slipping of the bars which occurred was not observed until the maximum load had been passed, and generally in these cases the crack also extended along the bars. It seemed evident to the observers that this slip did not occur before the maximum load was applied and before the existence of the diagonal crack had materially modified the conditions in the beam. Beams No. 66 and 67 (See Fig. 3 and 5) throw some light upon this matter. They were made for this purpose with very lean concrete and reinforced with corrugated bars. The condition of the beam at failure showed that the horizontal crack was due to vertical tension and that horizontal

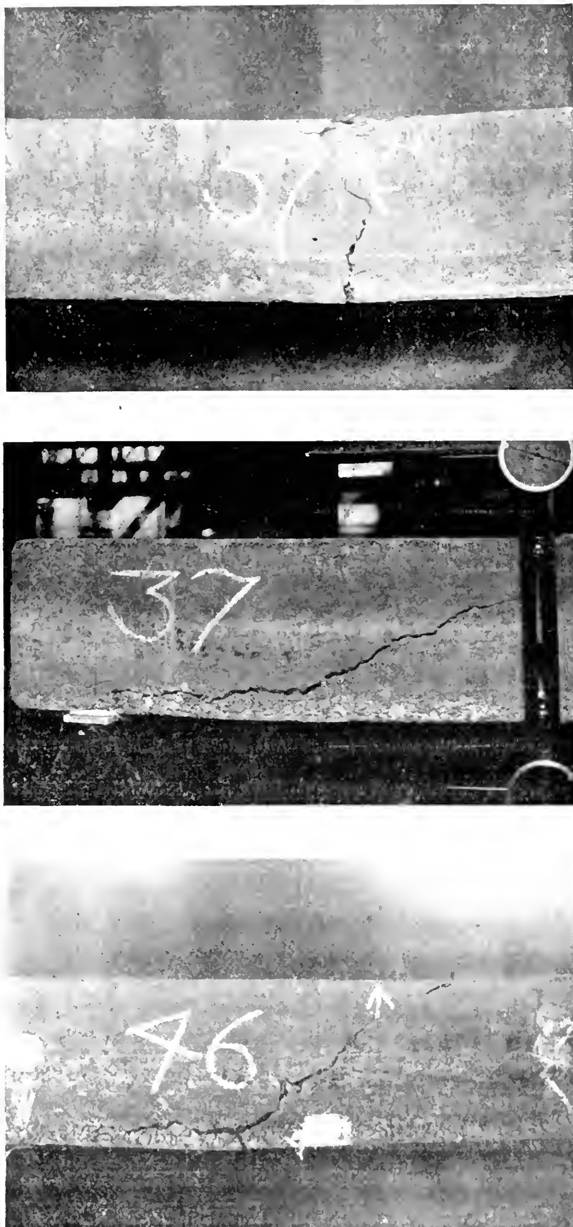


FIG. 4. VIEWS SHOWING BEAMS AFTER FAILURE.

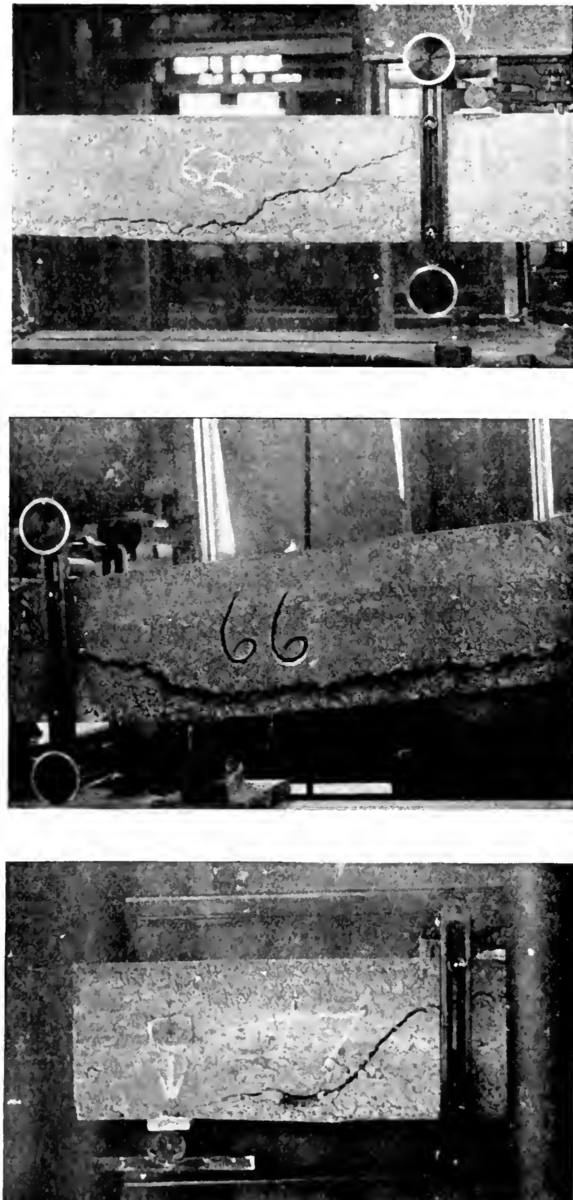


FIG. 5. VIEWS SHOWING BEAMS AFTER FAILURE.

FIG. 7. VIEWS SHOWING BEAMS AFTER FAILURE.

shear or slip did not take place until after this crack had been formed. The indentations in the concrete formed by the corrugations of the bars were left in perfect condition and there was no crushing or tearing at the edges of these indentations. The bar had simply been pulled down and out of the place in which it had rested. Comparisons with the results of beams made with the same concrete and with smooth steel (Beams No. 62, 63, and 71) show values almost identical and go to indicate that slipping had no part in the critical failure of the beams made up with smooth bars. In all the cases where slipping of the bar took place the action extended progressively from the diagonal

TABLE 11.

DIAGONAL TENSION FAILURES.

BARS BENT UP.

All beams loaded at one-third points.

Beam No.	Span ft.	Per cent Reinforcement	k	Maximum Applied Load lb.	Vertical Shearing Stress lb. per sq. in. $v = \frac{V}{bd'}$	Manner of Failure
			1-3-6 Concrete.			
7	10	0.98	.44	8370	69	Diagonal tension.
13	10	2.21	.75	9320	80	Diagonal tension.
14	10	2.21	.66	10560	89	Diagonal tension.
17	8	0.98	.46	9150	74	Diagonal tension.
20	6	0.98	.48	11620	90	Diagonal tension.
21	6	0.98	.48	16500	126	Diagonal tension.
22	6	0.98	.49	16760	128	Diagonal tension.
Av.	......	....	..	....	95	
			1-3-5½ Concrete.			
36	10	0.98	.58	7910	64	Diagonal tension
38	8	2.21	.70	11920	99	Diagonal tension
39	8	2.21	.73	14000	115	Diagonal tension
Av.	.....	....	......	....	93	

crack toward the load point, though in some cases this action was quite sudden. From all the information available it seems to be evident that, whatever slip of the bars may have taken place, the slipping did not exist before the time of the maximum load and resulted from the changed conditions incident to the formation of the diagonal crack. It therefore seems evident that the failure of these beams should be credited to diagonal tension.

Table 11 gives results of beams with reinforcing bars bent up, or inclined in the outer thirds of the length of the beam. The values of v are calculated by equation (18) and with d as 10 in., and hence do not give the actual amount of the shear. The amount and position of this bending have been described under "5. Test Beams". Fig. 6 gives the sketches of the appearance of

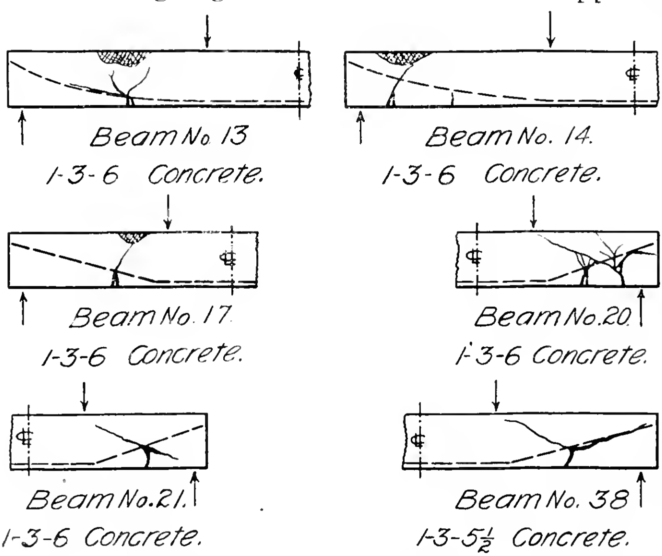


FIG. 6. SKETCHES SHOWING BEAMS AFTER FAILURE.

the crack after final failure or after the maximum load had been passed. The view of Beam No. 39, shown in Fig. 7, is from a photograph of the beam after failure. Generally speaking, the vertical portion of the crack from the bottom of the beam to the reinforcement formed first, and was due to the failure of the concrete in tension. The diagonal crack then grew toward the load point, generally forming before the maximum load was reached, and the growth of the crack along the reinforcing bar generally

followed. It was expected that this method of bending up bars would give a higher value for the vertical shear as calculated by equation (18) in beams failing by diagonal tension than that found in beams with the bars horizontal, but in this the results were disappointing. In a few beams the values ran higher. Comparing Beam No. 21 with Beam No. 22 it will be seen that no difference was observed whether part of the bars were bent up and part left horizontal, or all were bent up. The values of v for these beams were among the highest found with this quality of concrete. In the phenomena of failure it appeared that the element of slip was present, though it is not known that this slip occurred before failure. Calculations indicate that the bond stress developed at the end of the bars must have been considerable. It should be noted that none of the bars were anchored at the ends.

Table 12 gives the beams in which failure occurred by tension in the steel or compression of the concrete. It will be seen that the dimensions of these beams were such that the diagonal tension developed (as measured by the vertical shear) at the time of failure was less than was found with beams which failed in diagonal tension and hence that the strength of the concrete in diagonal tension had not been reached. Beam No. 35 which failed in compression, was of 1-4-7½ concrete, a very lean mixture. Beam No. 10 was one of the beams with poorly made concrete and in this case the inferior quality of the concrete was especially noticeable.

In Beams No. 68, 69, 70, 71, 72, and 73, U-shaped stirrups of ½-in. mild-steel round rods were placed in a vertical position and enveloped the horizontal reinforcing bars. The longitudinal spacing was inadvertently made 12 in. Beam No. 69 failed by tension in the steel at a value of v of 129 lb. per sq. in., which is below the resistances developed in the beams of 1-2-4 concrete which failed in diagonal tension, and the efficiency of the stirrups was not determined. Beams No. 72 and 73 also failed by tension in the steel at values of v below what was found in beams of 1-3-5½ concrete of the same quality which failed in diagonal tension. Beam No. 70 failed by compression of the concrete, but a diagonal crack had formed, before the maximum load was applied, at a value of v which is high for 1-3-5½ concrete, and the stirrups seemed to be effective in preventing sudden failure after the

TABLE 12.

MISCELLANEOUS FAILURES.

All beams loaded at one-third points.

Beam No.	Span ft.	Per cent Reinforcement	k	Maximum Applied Load lb.	Vertical Shearing Stress lb. per sq. in. $v=\frac{V}{bd'}$	Manner of Failure
			1-4-7½ Concrete.			
35	12	0.98	.68	7500	64	Compression.
			1-3-6 Concrete.			
4	12	0.98	.48	9360	78	Tension
10	12	0.98	.64	9430	77	Compression.
12	10	2.21	.79	10200	89	Compression
Av.	.....	....	....	......	81	
			1-3-5½ Concrete			
32	12	0.98	.57	9800	81	Tension.
74	10	0.98	.52	11950	95	Tension.
26	8	0.98	.51	14030	109	Tension.
Av.	.....	....	.....	....	95	
			1-2-4 Concrete.			
28	12	0.98	.36	9900	82	Tension.
31	12	0.98	.48	9400	79	Tension.
Av.	......	....	......	....	80	

maximum load was passed. Beam No. 68 (Fig. 7) failed in diagonal tension at a value of v of 115 lb. per sq. in. At a load of 13 000 lb. the diagonal crack extended 7 in., and at the maximum load, 14 220 lb., it extended to a point under the load point and

was $\frac{1}{32}$ in. wide. The load fell off very slowly, and the stirrups prevented sudden failure. Beam No. 71 (Fig. 7) failed by diagonal tension at a value of v nearly the same as the companion beams of 1-5-10 concrete which did not have stirrups. The load dropped off rapidly after the maximum load was reached and the stirrups seemed to have little effect. It is clear that the spacing of the stirrups in these beams caused them to be inefficient, the distance apart being too great, and besides, the stirrups were not properly placed in the beam. Further tests are now in progress, in which the dimensions of the beam and the size and spacing of the stirrups are expected to bring out the effectiveness of this method of metallic web reinforcement.

15. *Summary.*—The following summary of parts of the foregoing discussion is given:

1. For beams proportioned to give failure by tension in the steel reinforcement (i. e., when neither compression of concrete nor diagonal tension causes failure), those made with the richer concrete carried higher loads. The beams with 1-2-4 concrete carried loads greater by, say, 10%, than those with 1-3-5½ concrete.

2. In beams which failed by tension in the steel, the resisting moment developed was found to be about the same for loads applied at two points more or less far apart and at eight points (approaching a uniform load), thus confirming the general applicability of the ordinary beam theory to simple beams without end restraint or horizontal restraint for any of the ordinary methods of loading. For center loading the resisting moment developed ran 10% higher and in former tests even greater. This excess indicates a different distribution of stresses for center loading from that assumed in the ordinary beam theory.

3. The tests with repetitive loading are not conclusive and show the need of further investigation in this direction. The manner of failure in general was the same as may be expected with beams of the same reinforcement and same quality of concrete loaded progressively to final failure. Whether the maximum load carried in the case of this repetitive loading is less than would have been the case with progressive loading is not known, but there are some indications that the maximum load was less than it would have been without repetition. The in-

crease in the deflections of the beam with repetition of the load was marked, and the set in the beam was considerable. It should be remembered that the repetitive load was a considerable proportion of the maximum load finally applied and much higher than ordinary working loads. It seems evident that the amount of reinforcement for which the elastic tensile strength of the steel may be considered to balance the compressive strength of the concrete, (conveniently called the "balanced reinforcement"), should be taken at a lower percentage in beams subjected to a repetition of load than is found necessary in the case of beams tested by means of a gradually applied load, and that for the ordinary conditions of fabrication and use the "balanced reinforcement" selected should be much less than that determined by test beams.

4. The manner of failure depends not only upon the relative dimensions of depth and length of beam and the amount of reinforcement, but also upon the richness and strength of the concrete.

5. The loads carried by beams failing by diagonal tension depended both upon the richness of the concrete and upon its quality as influenced by the methods of mixing and storing. Poorly made concrete gave a vertical shearing stress averaging 71 lb. per sq. in. as compared with 99 lb. per sq. in. for well made concrete of the same mixture. The value, 138 lb. per sq. in., for the 1-2-4 concrete shows the advantage of the richer mixture.

6. Failure by diagonal tension generally occurs without warning, resembling somewhat in this respect the failure of unreinforced concrete beams. On account of the variability of concrete and its unreliability in resisting tensile stresses, relatively low diagonal tensile stresses (high factor of safety), as measured by the vertical shearing stresses, should be specified, unless there is effective metallic web reinforcement. The values allowed by many building ordinances seem too high to secure safety under the condition of ordinary building operations. Short, deep beams and beams restrained at the ends require that special attention be given to web stresses.

7. Slipping of bars and stripping of bars may accompany final failure of beams which fail by diagonal tension. It appears that slipping or stripping did not take place in the beams having the reinforcing bars horizontal until after the maximum load was

reached and the presence of diagonal cracks had modified the distribution of stresses. At these maximum loads the calculated bond resistance developed was low as compared with the bond strength of the steel and concrete. The beams reinforced with deformed bars carried no higher loads than those with plain bars. The beams with bars bent up or inclined toward the ends gave quite variable results, but in general the values were even lower than those with the bars in a horizontal position. There is some probability that slipping occurred in these tests at or before the maximum load and that anchoring the ends of the bars would have been beneficial. The results for the beams having vertical stirrups showed that the stirrups as used were not efficient in taking web stresses.

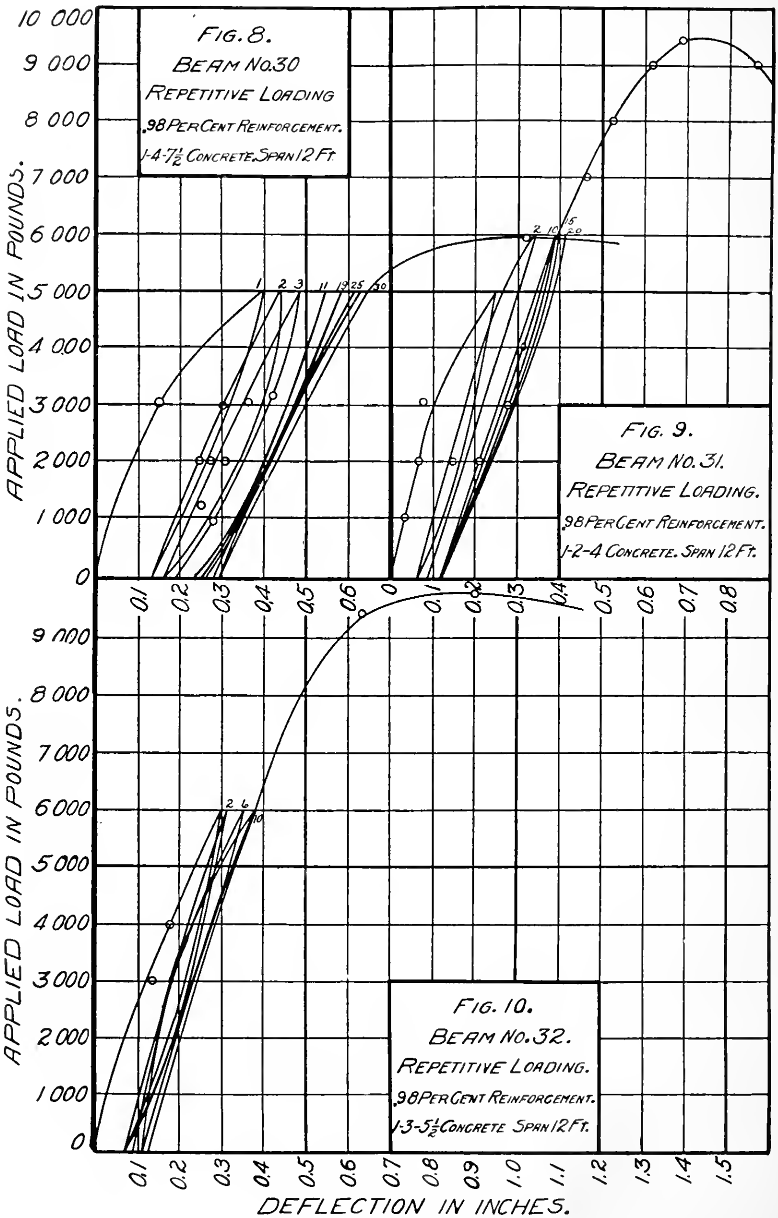


FIG. 8.
BEAM NO. 30
REPETITIVE LOADING
.98 PER CENT REINFORCEMENT.
1-4-7½ CONCRETE. SPAN 12 FT.
FIG. 9.
BEAM NO. 31.
REPETITIVE LOADING.
.98 PER CENT REINFORCEMENT.
1-2-4 CONCRETE. SPAN 12 FT.
FIG. 10.
BEAM NO. 32.
REPETITIVE LOADING.
.98 PER CENT REINFORCEMENT.
1-3-5½ CONCRETE SPAN 12 FT.
APPLIED LOAD IN POUNDS.
APPLIED LOAD IN POUNDS.
DEFLECTION IN INCHES.

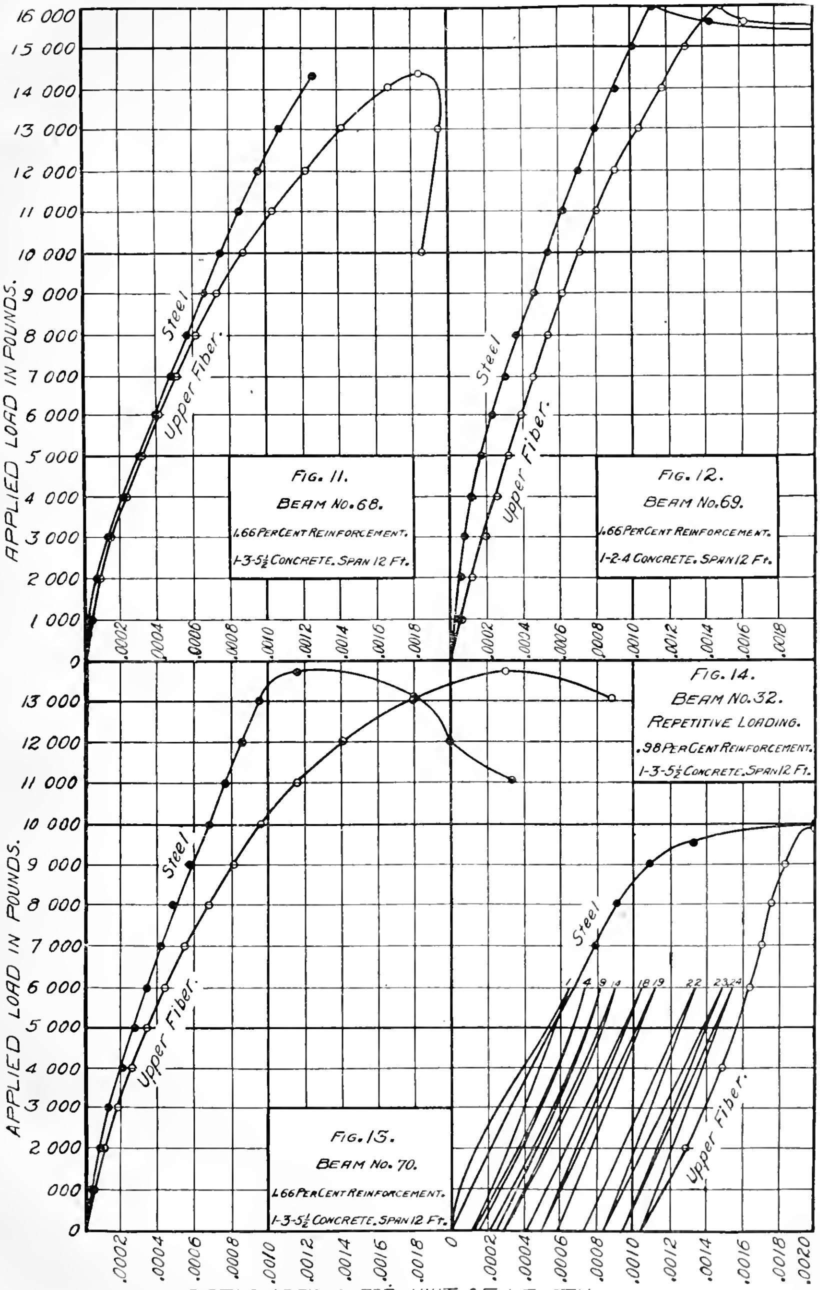


FIG. 11.
BEAM NO. 68.
1.66 PER CENT REINFORCEMENT.
1-3-5½ CONCRETE. SPAN 12 FT.
FIG. 12.
BEAM NO. 69.
1.66 PER CENT REINFORCEMENT.
1-2-4 CONCRETE. SPAN 12 FT.
FIG. 13.
BEAM NO. 70.
1.66 PER CENT REINFORCEMENT.
1-3-5½ CONCRETE. SPAN 12 FT.
FIG. 14.
BEAM NO. 32.
REPETITIVE LOADING.
.98 PER CENT REINFORCEMENT.
1-3-5½ CONCRETE. SPAN 12 FT.
Steel
Upper Fiber.
APPLIED LOAD IN POUNDS.
DEFORMATIONS PER UNIT OF LENGTH.

Publications of The Engineering Experiment Station

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (*Out of print*).

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (*Out of print*).

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (*Out of print*).

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

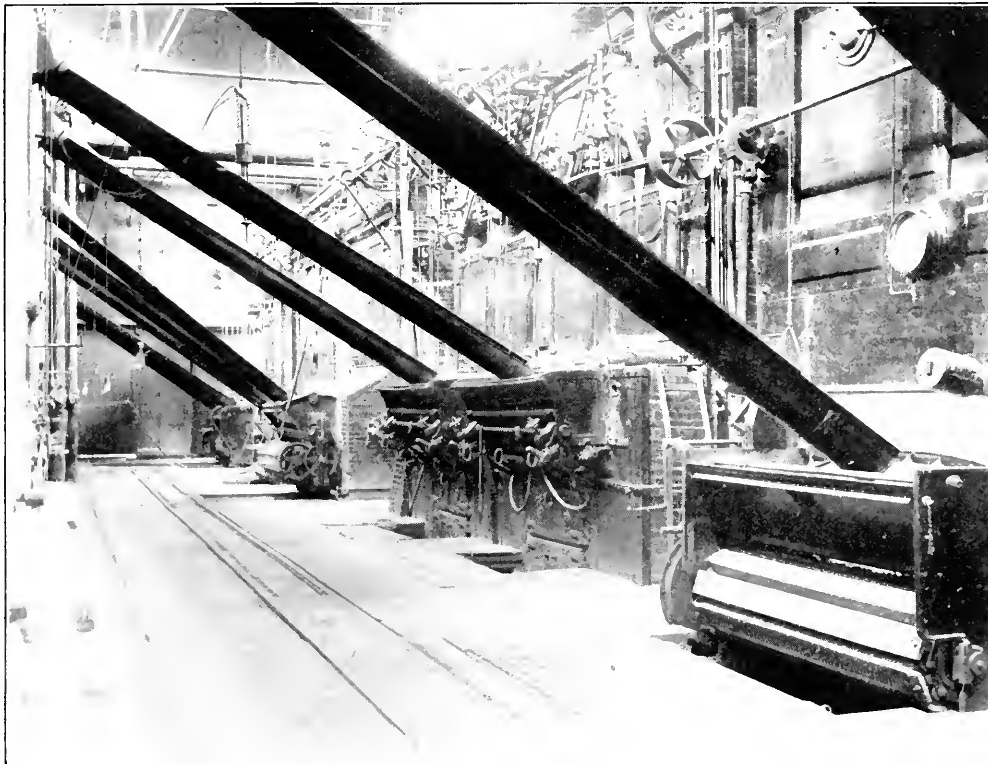
Bulletin No. 10. Tests of Plain and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.

Bulletin No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.

Bulletin No. 14. Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907.



View in Central Heating Station University of Illinois

UNIVERSITY OF ILLINOIS

ENGINEERING EXPERIMENT STATION

BULLETIN NO. 15 AUGUST 1907

HOW TO BURN ILLINOIS COAL WITHOUT SMOKE

BY L. P. BRECKENRIDGE, DIRECTOR OF THE ENGINEERING EXPERIMENT STATION

It is the intention to discuss in this paper the fundamental principles that apply to smokeless furnace construction and operation and to illustrate by means of units in actual operation several ways in which these principles have been satisfactorily applied. With a clear idea of the principles involved, with a knowledge of the character of the coal to be used and the capacity at which it is desired to drive the furnace, there should be little difficulty in designing, constructing and operating stationary boiler furnaces which under ordinary conditions of service will operate with high economy and which will burn Illinois coal without smoke.

The writer does not profess to be acquainted with all the methods that have been found satisfactory for the purpose of smoke prevention, neither does he consider it advisable to describe in detail all the furnaces that are claimed to be capable of burning coal without smoke. All that can be attempted here will be a description of those furnaces with which the writer is personally familiar or which have been examined while in operation and have been found to give satisfactory results.

Perhaps the one thing that has most delayed progress toward success in the smokeless operation of furnaces is the fact that in the past so much in their operation has depended upon the human element. It will doubtless be found that those plants smoke less that are mechanically operated. Such operation is by no means a sure preventive of smoke, as certain constructive features are now well recog-

nized as necessary even with good mechanical stokers if smokeless combustion is to be obtained.

This discussion will be confined to those settings and furnaces that have been found to be most satisfactory in burning Illinois coals without smoke. From a study of the tests of the various coals of the United States, as presented in the reports of the United States Geological Survey fuel testing plant, it seems safe to say that engineers now have sufficient information available to enable them to design boiler furnaces that will burn any coal without smoke. The progress made in this direction during the last five years is surely encouraging and it is confidently believed that the time will soon come when no power plant can offer as an excuse for a smoky chimney the plea that no appliances are available which can be depended upon for smoke prevention. The problem of smoke prevention is the problem of perfect combustion. There is no such thing as smoke consumption and this term should never be used. There is such a thing as perfect combustion and this means smokeless combustion.

The Principles of Smokeless Combustion

The subject of combustion should be familiar to all mechanical engineers. However, as a basis for a thorough understanding of the problems of smoke prevention, a brief review of the principles of combustion may prove acceptable in connection with this subject. In fact, the complete solution of the smoke problem consists in providing furnaces, so constructed and so capable of operation as to make combustion nearly perfect.

Combustion may be defined as a rapid chemical combination, resulting in heat and light. The combining elements are: (a) Oxygen, which is usually derived from atmospheric air; (b) Either carbon or

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This bulletin was prepared at the suggestion of the Conference Committee on Fuel Tests, the members of which are given below. It should be stated, however, that the Committee is in no way responsible for the opinions expressed by the writer.

H. Foster Bain, Director State Geological Survey, Urbana, representing the State Geological Survey; A. Bement, Consulting Engineer, Chicago, the Western Society of Engineers; Edwin H. Cheney, President Fuel Engineering Co., Chicago, the Building Managers' Association of Chicago; F. H. Clark, Supt. Motive Power Burlington Road, C. B. & Q. Ry., Chicago, the Western Railway Club; Adolph Mueller, President H. Mueller Mfg. Co., Decatur, Ill., the Illinois Manufacturers' Association; Carl Scholz, President Coal Valley Mining Co., Chicago, the Illinois Coal Operators' Association; Wm. L. Abbott, Chief Operating Engineer Chicago Edison Co., Chicago, the Board of Trustees, University of Illinois; L. P. Breckenridge, Director Engineering Experiment Station, University of Illinois, Urbana, Ill.

hydrogen, or a compound of the two. Sulphur sometimes appears with carbon and hydrogen, and also combines with oxygen. The substance that is formed by the chemical union is called the product of combustion; and the heat that is produced by the combustion of a unit weight (one pound) of the fuel is called the heat of combustion. This is usually measured in British thermal units (B. t. u.). One B. t. u. is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. The following table relates to the complete combustion of hydrogen, carbon and sulphur:

COMPLETE COMBUSTION OF THREE ELEMENTS

		PRODUCT OF COMBUSTION		
Element	Chemical Symbol	Name	Chemical Symbol	Heat of Comb'st'n B. t. u. per lb.
Hydrogen	H	Water	H_2O	62000
Carbon	C	Carbon Dioxide	CO_2	14500
Carbon	C	Carbon Monoxide	CO	4400
Sulphur	S	Sulphur Dioxide	SO_2	4000

In the complete combustion of carbon, the product of combustion, it will be observed, is carbon dioxide (CO_2). Each atom of carbon combines with two atoms of oxygen. If sufficient oxygen is not provided, it may happen that each carbon atom will combine with but one oxygen atom, thus forming carbon monoxide (CO). As a result of this incomplete combustion, the heat developed is only 4400 B. t. u. The carbon monoxide may itself combine with oxygen, according to the formula

$$CO + O = CO_2$$

and the heat developed will be the difference, $14\,500 - 4400 = 10\,100$ B. t. u. per pound of carbon in the carbon monoxide.

A knowledge of the relative weights of these elementary atoms gives a direct means of computing the amount of oxygen required for combustion. The weights are as follows:

H..........1	O..........16
C..........12	S..........32

In the burning of hydrogen to H_2O, two atoms of hydrogen, each of weight 1 combine with one atom of oxygen, weight 16; hence the ratio of oxygen to hydrogen is $16 : 2 = 8 : 1$, i.e., 8 lb. of oxygen are required for the combustion of 1 lb. of hydrogen, and

there results 8 + 1 = 9 lb. of water. This combination with others may conveniently be presented in a tabular form as follows:

THE COMBUSTION OF IMPORTANT ELEMENTS WITH OXYGEN

Elements	Chemical Equation	Relative Weights	Weights pounds
Hydrogen to H_2O	$2H + O = H_2O$	$(2 \times 1) + 16 = 18$	$1 + 8 = 9$
Carbon to CO_2	$C + 2O = CO_2$	$12 + (2 \times 16) = 44$	$1 + 2\frac{2}{3} = 3\frac{2}{3}$
Carbon to CO	$C + O = CO$	$12 + 16 = 28$	$1 + 1\frac{1}{3} = 2\frac{1}{3}$
Sulphur to SO_2	$S + 2O = SO_2$	$32 + (2 \times 16) = 64$	$1 + 1 = 2$
Methane or Marsh Gas	$(CH_4) + 4O = CO_2 + 2H_2O$	$(12 + 4) + (4 \times 16 = 12 + (2 \times 16) + 2(2 + 16)$	$1 + 4 = 2.75 + 2.25$

When the oxygen needed for combustion is taken from the atmosphere, the nitrogen always present must be taken into consideration. Nitrogen takes no part in the combustion but mingles with the products of combustion, absorbs heat from them and passes away with them. Approximately, it takes 4.25 lb. of air to furnish 1 lb. of oxygen; the remaining 3.25 lb. are nitrogen. When the combustion of the different elements takes place in air the resulting relative weights are modified on account of the presence of the nitrogen. This is exhibited below.

THE COMBUSTION OF IMPORTANT ELEMENTS IN AIR

Elements	Chemical Equation	Relative Weights	Weights pounds
Carbon in Air	$C + Air = CO_2 + 7.43N$*	$12 + (2 \times 4.25 \times 16) = 44 + 104$	$1 + 11.33 = 3.67 + 8.66$
Marsh Gas in Air	$CH_4 + Air = CO_2 + 2H_2O + 14.86N$	$(12 + 4) + (4 \times 4.25 \times 16) = 44 + (2 \times 18) + 208$	$1 + 17 = 2.75 + 2.25 + 13$

* The atomic weight of nitrogen is 14.

It will be seen from the above table that to burn 1 lb. of carbon 11.33 lb. of air must be supplied. The 8.66 lb. of nitrogen contained in the weight of air pass away with the 3.67 lb. of carbon dioxide (CO_2) formed by the combustion. For the complete combustion of 1 lb. of marsh gas, 17 lb. of air are required. Chemical combinations of carbon and hydrogen, the so-called hydrocarbons, play an important part in the burning of coal, particularly in those coals of large volatile content. The most important of these are the following:

Hydrocarbon Element	Chemical Symbol	Heat of Combustion
Methane or Marsh Gas	CH_4	24020 B. t. u.
Ethylene or Olefiant Gas	C_2H_4	21930 B. t. u.
Acetylene	C_2H_2	21850 B. t. u.

At the ordinary temperature and atmospheric pressure, a pound of air has a volume of about 13.1 cu. ft. Using this value, the following (round numbers) are obtained for the theoretical amount of air required for the complete combustion of various fuels:

AMOUNT OF AIR REQUIRED TO BURN ONE POUND OF VARIOUS FUELS

Kind of Fuel	Carbon	Hydrogen	Sulphur	Methane
Weight of Air (lb.)	11.33	34	4.25	17
Volume of Air (cu. ft.)	150	445	55	220

The heat developed by the combustion is absorbed by the products of combustion, and as a result, the temperature of these gases rises in a marked degree. Thus when carbon is burned in air, the 14 500 B. t. u. developed should heat the 3⅔ lb. of CO_2 and 8⅔ lb. of nitrogen from an initial temperature of perhaps 60° to a calculated final temperature of about 4500°. The actual final temperature, for reasons to be explained presently, is considerably lower. The products of combustion act as a vehicle, carrying the heat developed by combustion to its final destination.

It may perhaps be profitable to picture an ideal perfect combustion, and then inquire in what ways actual combustion falls short of the ideal. The given fuel, composed of carbon, various volatile hydrocarbon gases, and perhaps sulphur, is to be burned in air. Theoretically, each atom of the fuel finds and seizes upon the number of oxygen atoms with which it will combine. Each atom will meet with two oxygen atoms at a temperature sufficiently high for ignition. They will combine, and the resulting CO_2 will pass out of the furnace, carrying with it the heat arising from the combustion; likewise with the hydrogen and sulphur atoms. No more air will be delivered than is just sufficient to furnish the exact number of oxygen atoms, and no carbon or hydrogen atoms will pass out of the furnace without finding oxygen atoms with which they can combine.

Actual combustion deviates from ideal conditions in many respects. If only the theoretical amount of air is supplied, on account of the difficulty of properly mingling the fuel and air, some of the fuel atoms will not find oxygen atoms, and will escape uncombined. Or some of the carbon may burn to carbon monoxide instead of to carbon dioxide, and the CO will escape without further combustion. It is found in practice that to insure complete combustion, an excess of air must be furnished. This excess is usually 50 per cent, and may reach 100 per cent; i.e., while only 11.3 lb. of air are required for the com-

plete combustion of 1 lb. of carbon, it is usually necessary to furnish 18 to 24 lb. Since the heat of combustion is distributed throughout the excess of air introduced into the furnace as well as the products of combustion, the furnace temperature is lowered by the presence of the extra air.

In another important particular, the actual state of affairs is likely to be quite different from the ideal combustion outlined above. Carbon and oxygen atoms will not unite unless a certain temperature, the ignition temperature, is reached. In parts of the furnace, the temperature may fall below the ignition point because of the inrush of an excess of air, or because of cold bounding surfaces. As a result, carbon particles, even in the presence of plenty of oxygen, will refuse to burn. Let us further illustrate these principles by the use of some familiar examples.

If the reader understands why a torch smokes, why a flat wick is used in a lamp, why a circular burner is provided for the Argand or student lamp, why a chimney is provided for oil lamps, why a fish tail flame was used in early gas lighting, or why a vacuum bulb is provided for the incandescent lamp; if he understands these things, and most of us do, he will, it is believed, be able easily to see what conditions are necessary for perfect combustion in boiler furnaces.

If any fuel is to be burned without smoke it must be supplied with the correct amount of air. The torch smokes because the large round wick brings up oil, especially in the center, to which air cannot be supplied. If the air supply through the center tube of our student lamp is shut off a smoking flame results. The candle with the small wick is an advance over the candle supplied with the large wick. The flame from the flat wick has an extended surface for air supply, while the circular burner not only has maximum surface for air supply, but the air coming up through the center of the tube is heated, making it still better suited to aid combustion and burn a large amount of oil. Thus it is that we have successfully solved the problem of burning a large oil supply without smoke. If we try to increase the oil consumption and turn up our lamps too high, they smoke, and because they are in the room with us we immediately turn them down. Furnaces burning coal sometimes smoke just because they are forced too hard, and because the top of the chimney is not in our room, but in the public's pure air we do not turn them down, but let them smoke.

Air correct in amount is a necessity for complete combustion and the simple experiments which we have all been making with our oil and gas flames should be sufficient evidence to us that only when we are able to supply our furnaces with the correct amount of air shall we be able to control the smoke which it is so easy to make. How much easier our problem would be if, as in the lamp, we could see all that was taking place and could regulate all by a simple knurled brass handle.

Smoke Production

Having briefly outlined the essential features of perfect combustion let us turn our attention to the conditions present when the combustion is imperfect, usually resulting in smoke. The products of combustion, carbon dioxide, steam and sulphur dioxide are colorless gases. If nothing except these gases escaped from a chimney, there would be no smoke problem. Visible smoke is due to the volatile hydrocarbons which all bituminous coal contains to a greater or less extent, and which are driven off when the coal is heated. The percentage of volatile matter in coal varies widely; thus in the eastern anthracites, it may be as low as 3 per cent, while in the western lignites, it may rise as high as 50 per cent. The larger the percentage of volatile matter, the more liable is the coal to produce smoke, and the more difficult is smoke prevention.

When coal is heated in the furnace, the volatile content, consisting largely of methane and ethylene, is driven off. If the volatile gases should not enter any region of high temperature, they would simply pass out of the chimney with the products of combustion. But, as a rule, the gases are ignited, and burn, much as ordinary illuminating gas burns. The phenomena connected with the combustion of volatile gases are, however, not simple. There are grounds for supposing that a hydrocarbon, at a sufficiently high temperature, is decomposed into its elements. If oxygen is present, the hydrogen at once combines with it. The carbon particles will not combine with oxygen except under favorable conditions; if there is not a sufficient supply of air, or if it is not at a sufficiently high temperature, the carbon particles refuse to combine and are carried along with the products of combustion to be afterwards deposited as soot, or appear at the top of the chimney as smoke. This may be shown by an equation as follows:

$$C_2H_4 + 2\,O = 2H_2O + 2\,C$$

Ethylene and oxygen form water vapor and soot.

The mere explanation of the formation of black smoke suggests immediately the means that should be employed to prevent such formation. Evidently sufficient air must be furnished to burn the carbon particles liberated from the hydrocarbon gases; this air must be at a high temperature. If too great a volume of cold air is admitted to the furnace, and if at the same time the bounding surfaces of the combustion space are boiler plates or tubes of relatively low temperature, the result will be a low temperature in the space above the fuel, and it will be impossible to burn the carbon content of the volatile matter. To insure proper combustion, after the gases are driven from the coal, they should intimately mingle with sufficient air in a chamber, in which high temperature can be maintained. The heating surface of the boiler should not be permitted to come in contact with these gases until combustion has been completed.

Losses Due to Smoking Chimneys

The destruction of property or the effect upon the health of the community due to the smoke nuisance are matters upon which there is not an opportunity to dwell in this article. Both of these subjects are now matters of common every-day knowledge to the residents of our American cities. Something should be said, however, about the fuel losses due to smoking chimneys. The absence of smoke by no means indicates perfect combustion. It may simply mean excessive air dilution and this means uneconomical operation. Statements are frequently seen in the daily press to the effect that one-quarter or one-third of the fuel burned goes off in the black smoke issuing from the chimney. Such statements are very far from the truth. It is doubtful if the black carbon particles which issue from chimneys and which we call soot ever amount to one per cent of the fuel burned in any furnace. It takes but a small amount of soot to give a dense black color to smoke. If it were to save only these soot particles we could not afford expensive stoker and furnace settings. The appearance of black smoke is fortunately the signal of incomplete combustion and the losses due to this cause are many times the losses due to the carrying away of the small soot particles. This matter is well stated by that practical and clear writer, Wm. H. Booth, as follows:

"It is customary to speak of smoke and the smoke nuisance as though black smoke were the only feature of imperfect combustion

that demanded a remedy. But it cannot be too strongly emphasized that the visible impurities of the waste gases from factory chimneys are the least harmful part of their constituents; and that the invisible gases, which too often escape as the result of imperfect combustion, are far more detrimental in their effects upon vegetation and upon the health of the community. These invisible gases consist of unaltered hydrocarbons and of carbon monoxide; their presence is due either to deficiency of air, or to the lack of the requisite temperature in the combustion area. Smoke is the visible sign of the presence of these deleterious gases. It is, therefore, a useful signal of something wrong in the combustion process. Smoke ought to be attacked, not only because it brings dirt and depression in its train, but because its emission is accompanied by that of gases which are directly detrimental to the health of all living things, and at the same time carry away much heat from the plant of the fuel user. Both on humanitarian and economic grounds its suppression is called for*."

If there is a deficient air supply part of the carbon atoms will not find enough oxygen atoms with which to combine and there will be a considerable part of the escaping gases leaving the chimney as carbon monoxide (CO) instead of being burned to carbon dioxide (CO_2). For each pound of carbon burned only to carbon monoxide (CO) there will be a loss of approximately 10 000 heat units and this constitutes the great source of loss so frequently referred to as the loss due to incomplete combustion. This loss may readily amount to 5 per cent of the total heat in the coal. The density of the accompanying smoke may or may not be an indication of the proportion, though the loss due to carbon monoxide in perfectly smokeless chimney gases in practice will usually not exceed 0.05 of one per cent. Smokelessness is a relatively safe indication that the total heat has been liberated. Unfortunately it gives no indication of the degree of efficiency with which the heat is being utilized. The problem from the standpoint of the operator demands smokelessness with a minimum air supply. Losses due to sensible heat in the stack gases while seldom rising higher than 32 per cent of the total heat may be as low as 10 to 12 per cent without smoke or incomplete combustion. These figures are found in the fuel test reports of the United States Geological Survey under Illinois coals. The following tabulation will serve to indicate

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SMOKE PREVENTION AND FUEL ECONOMY, Booth and Kershaw—Archibald, Constable & Co., London, 1904.

how the heat generated in a boiler furnace may be distributed when operating under poor, average and best conditions.

AN APPROXIMATE HEAT DISTRIBUTION FROM ILLINOIS COAL

	PERCENTAGE OF HEAT		
	1 Poor Condition	2 Average Condition	3 Best Condition
1. Absorbed by the boiler	50.0	65.0	75.0
2. Carried away in dry chimney gases	24.0	16.0	10.0
3. Radiation and unaccounted for osses	15.0	12.0	10.0
4. Moisture formed by burning of hydrogen	4.0	3.5	3.0
5. Evaporating moisture in coal	2.0	2.0	1.5
6. Incomplete combustion of carbon	5.0	1.5	0.5
Total heat	100.0	100.0	100.0

The per cents given in the last column of this tabulation are seldom attained in present practice, but they are by no means impossible. They represent conditions for which we should continually strive. Losses of 20 to 25 per cent are not unusual, both with and without smoke. Too little air is wrong. Too much air is wrong. Absolutely complete combustion can be obtained using Illinois coal burned on an automatic stoker with as low as 30 per cent excess of air. The question is one of proper furnace construction to meet the requirements of the fuel coupled with a good fireman and an intelligent use of instruments which will tell him at all times the conditions of the combustion and draft.

It has been stated elsewhere, what relation should exist between the weight of coal burned and the weight and volume of air required for perfect combustion. It is sometimes more striking, however, to bring out this point, by using a larger unit than the single pound. Take for instance, a 1000 horse-power boiler plant. Many such plants would burn 5000 lb. of coal an hour; the air supplied would weigh 100 000 lb. and the volume of this air at a chimney temperature of 500 degrees Fahr. would be about 2 400 000 cu. feet. The chimney for this plant must therefore discharge nearly 105 000 lb. (52.2 tons) of gases into the atmosphere each hour; that is, for each ton of coal burned the chimney will discharge from 18 to 22 tons of gases. To keep these gases of the right color and composition for 90 per cent of the time is the problem to be solved. Chimneys will still be needed when the so-called smoke problem is solved. The popular solution consists

in changing the color of the gases flowing from the chimney from black to a light gray, that is from No. 5 to No. 1 on the Ringelmann chart. At least this is all that the public and the smoke inspector will demand. But even when this problem is well solved our chimneys must continue to discharge immense volumes of heated gases, and these gases will often carry with them fine particles of ash which cannot be burned; all of which may produce something of that disagreeable haze which floats over manufacturing cities. The dense black smoke from chimneys is certainly a nuisance. It can be stopped for about 90 per cent of the time, and if this is accomplished a most wonderful improvement will be observed in the atmosphere of our cities. If smoke is not largely prevented in large cities it will be because of laxity in carrying out the provisions of the law, combined with the indifference of power plant owners, rather than because of a lack of furnaces and boiler settings which are available for successfully burning bituminous coal without smoke.

The Observation of Smoke

From the point of view of the general public there are but two kinds of chimneys, those that smoke and those that do not smoke. The emission of black smoke for a short period say of three minutes of an hour is sometimes enough to leave the impression on the casual observer that the chimney smokes all the time. It is therefore important that there should be some way devised for estimating the relative blackness of smoke and some plan adopted for recording the length of time during which smoke of varying degrees of blackness is emitted from chimneys. Numerous schemes have been proposed to accomplish this purpose. One of the most scientific of these plans is that invented by Professor Ringelmann of Paris.*

"In making observations of the smoke proceeding from a chimney, four cards ruled like those in the cut, (See Fig. 1), together with a card printed in solid black and another left entirely white, are placed in a horizontal row and hung at a point about 50 feet from the observer and as nearly as convenient in line with the chimney. At this distance the lines become invisible, and the cards appear to be of different shades of gray, ranging from very light gray to almost black. The observer glances from the smoke coming from the chimney to the cards, which are numbered from 0 to 5, determines which card most nearly

* Trans. A. S. M. E., Vol. XXI, Dec., 1899.

corresponds with the color of the smoke, and makes a record accordingly, noting the time. Observations should be made continuously during say one minute, and the estimated average density during that minute recorded, and so on, records being made once every minute. The average of all the records made during a boiler test is taken as the average figure for the smoke density during the test, and the whole of the record is plotted on cross section paper, (See Fig. 2), in order to show how the smoke varied in density from time to time. A rule by which the cards may be reproduced is given by Professor Ringelmann as follows:

Card 0. All white.

Card 1. Black lines 1 mm. thick, 10 mm. apart, leaving spaces 9 mm. square.

Card 2. Lines 2.3 mm. thick, spaces 7.7 mm. square.
Card 3. Lines 3.7 mm. thick, spaces 6.3 mm. square.
Card 4. Lines 5.5 mm. thick, spaces 4.5 mm. square.
Card 5. All black.

The cards as printed on page 13 are much smaller than those used by Professor Ringlemann. The thickness and spacing of the lines are in the same proportion, but reduced to one-half size."

The smoke observations reported in the government fuel tests made by the Technologic Branch of the U. S. G. S. are all based on the Ringelmann chart. This chart has, therefore, been adopted in the reports of fuel tests made by the Engineering Experiment Station and the numbers used in its bulletins refer to this scale.

An observer soon becomes skilled in taking smoke records and when several observers have been trained to the system their records are very nearly alike. In fact one soon becomes so familiar with the scale of densities that he no longer needs the actual charts for comparison, but may be trusted to take the record without the aid of the chart. An attempt has been made to illustrate smoke densities in the plate shown in Fig. 2. Many difficulties surrounded the preparation and printing of such a plate and it is inserted with some misgivings. It is believed, however, that if it should prove successful it will give some reader a better idea of the value of the scale numbers 1 to 5, used to denote smoke densities than will the pictures of the Ringelmann charts.

When a record of a smoking chimney is desired numerous ways are adopted for showing its behavior. For many records a column of the scale density numbers is sufficient, set of course opposite the inter-

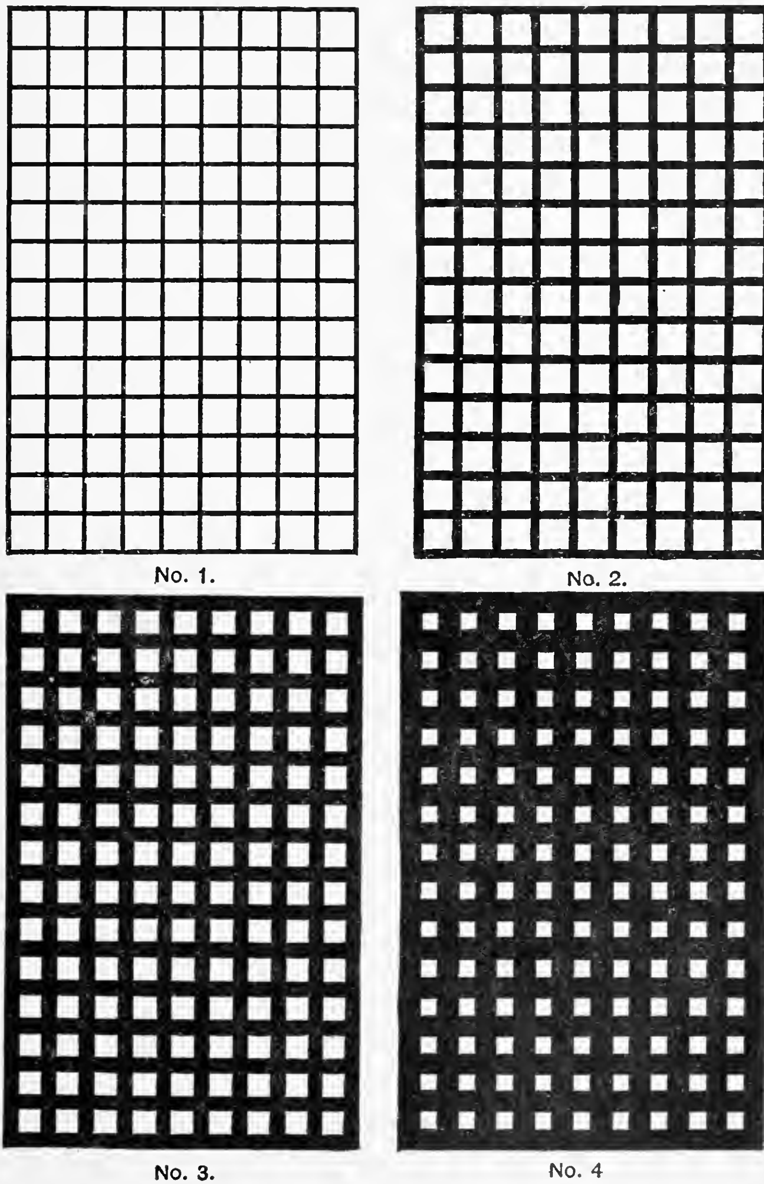

FIG. 1 THE RINGELMANN SCALE FOR GRADING THE DENSITY OF SMOKE

vals of time which are deemed short enough for the purpose for which the observations are taken. Where many records must be taken the work may be facilitated by using some of the simple mechanical devices which have been perfected for this purpose. These usually consist of a drum rotated by clockwork, and a marking pen movable by hand leaving a record on suitable paper that has been wrapped on the drum. The form of smoke chart record adopted in the work of the Engineering Experiment Station is shown in Fig. 3. This form needs little explanation. The scale density numbers are those at the left of the sectioned plates and these densities are approximately shown at the top under their respective numbers. It is intended that the time scale shall be chosen and placed along the zero horizontal lines. This time scale will vary according to the character of the tests being made. Graphic charts are for many purposes much preferable to any other scheme for exhibiting the continuous operation of chimneys supposed or claimed to be smokeless, and they are particularly useful when comparing several stacks for the same interval of time, or when changes made in a setting are being studied.

Furnaces and Boiler Settings Suitable for Burning Illinois Coal Without Smoke

General Principles of Construction.—Various writers on boilers and furnaces have enunciated the principles of smoke prevention in different ways. In "Steam Boiler Economy," Wm. Kent says:

"Coal can be burned without smoke provided:

(a) The gases are distilled from the coal slowly.

(b) That the gases when distilled are brought into intimate contact with very hot air.

(c) That they are burned in a hot fire-brick chamber.

(d) That while burning they are not allowed to come in contact with comparatively cool surfaces, such as the shell or tubes of a steam boiler; this means that the gases shall have sufficient space and time in which to burn before they are allowed to come in contact with the boiler surfaces."

Mr. A. Bement, who has made a careful study of the smoke problem, suggests* some slight modifications of the Kent form of statement. He says: "Professor Kent's requirements may be modified as to two features as follows:

*The Suppression of Industrial Smoke with Particular Reference to Steam Boilers.—Journal Western Society of Engineers. Dec., 1906.

(a) That the evolution of gas from the coal shall proceed uniformly.

(b) That the gases which are distilled uniformly from the coal shall enter a fire-brick chamber of either sufficient length to allow the flames to become entirely consumed naturally or that the chamber be provided with such auxiliary mixing and baffling devices as will cause the gases to be artificially mixed together before the exit of the chamber is reached."

Further discussing the subject, Mr. Bement presents clearly the importance of uniformity of the evolution of the volatile gases and points out that the lack of uniformity of the evolution of the gases when coal is hand-fired must be supplemented by efficient mixing devices such as fire brick piers or special baffling. The matter presented in this bulletin only corroborates the testimony presented in Mr. Bement's article, and except for the fact that possibly this publication may reach a larger number of manufacturers throughout the state than will Mr. Bement's paper, it need hardly have been presented.

Any fuel may be burned economically and without smoke if it is mixed with the proper amount of air at a proper temperature.

This is the statement of the smoke problem that the writer has sometimes presented. We have then three forms of presentation of the problem. To the fuel expert any one of these forms is sufficiently clear. It does, however, require some familiarity with the problem to understand just what these statements mean. To the owner who is trying to make his plant stop smoking or who must decide between several types of furnaces or boilers that he wishes to install, all these carefully stated formulas are often meaningless and provoking. What the owner wishes to know is what furnaces and boilers are in the market that are really suitable for burning Illinois coals without smoke. It is in many ways unfortunate that there are so many independent manufacturers of furnaces and boilers. Both furnace and boiler should preferably be sold and installed by the same company. It may not be long before this will be so. At least, the boiler companies should furnish complete plans with their boilers including the furnace. Possibly

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The Peabody Atlas—Shipping Mines and Coal Railroads in the Central Commercial District of the United States, with Chemical, Geological and Engineering Data. A. Bement, 1906. $16\frac{3}{4} \times 18$ in. 149 pp. An extensive and valuable work relating to the central coal fields of the United States, published by the Peabody Coal Co., Chicago. The section devoted to smokeless furnaces and smoke suppression contains many excellent illustrations which should be of great help to engineers who wish to be fully informed on this subject.

this matter might be left to the consulting engineers, but many firms buy their boilers directly from the boiler companies and follow the same setting plans that have been developed and found efficient with anthracite or other eastern coals, and often these are entirely unsuited for Illinois coals having such a high volatile content.

Much confusion has doubtless arisen and many disappointments have followed because of the fact that furnaces found entirely suitable for eastern coals have been tried further west without modification and have proved themselves failures. Some of the furnaces described in this paper would not be suitable for use with eastern coals. The use of the Dutch oven furnace, which was common before the chain grate stoker, doubtless paved the way for the various forms of automatic stokers which made use of the good points recognized in the old forms of the Dutch oven furnaces.

The history of the growth and development of the smokeless furnace could well form the subject for an engineering article. It is hoped that some one may soon make the steps in such a development a matter of record. The writer certainly makes no claims for discovery of invention in this connection. He has, however, experimented with many methods of firing, many devices for smoke prevention and many variations in furnace construction, not only in Illinois, but also in Pennsylvania and in New England.

The boiler plant at the University of Illinois at Urbana, Illinois, consists of 2000 horse-power in nine units. During the last two years this plant has been operated practically without objectionable smoke fully 90 per cent of the time. Over 200 separate boiler tests have been made in this plant to determine the economy of operation and for a study of furnace conditions. Many changes have been made in the constructive features of the furnaces and boiler baffling with the view of studying the smoke problem. Many varieties of coals have been tested for smokelessness. The character of the installation is indicated below.

Boiler No. 1. Babcock & Wilcox (Special high-pressure boiler 275 lb.), equipped with B. & W. chain grate stoker, usual vertical baffling, capacity 150 H. P. This unit can be run without smoke at capacities from 50 to 120 per cent.

Boiler No. 2. Babcock & Wilcox standard boiler (150 lb.) equipped with B. & W. chain grate stoker, usual vertical baffling, capacity 150 H. P. This unit can be run without smoke at capacities from 50 to 120 per cent.

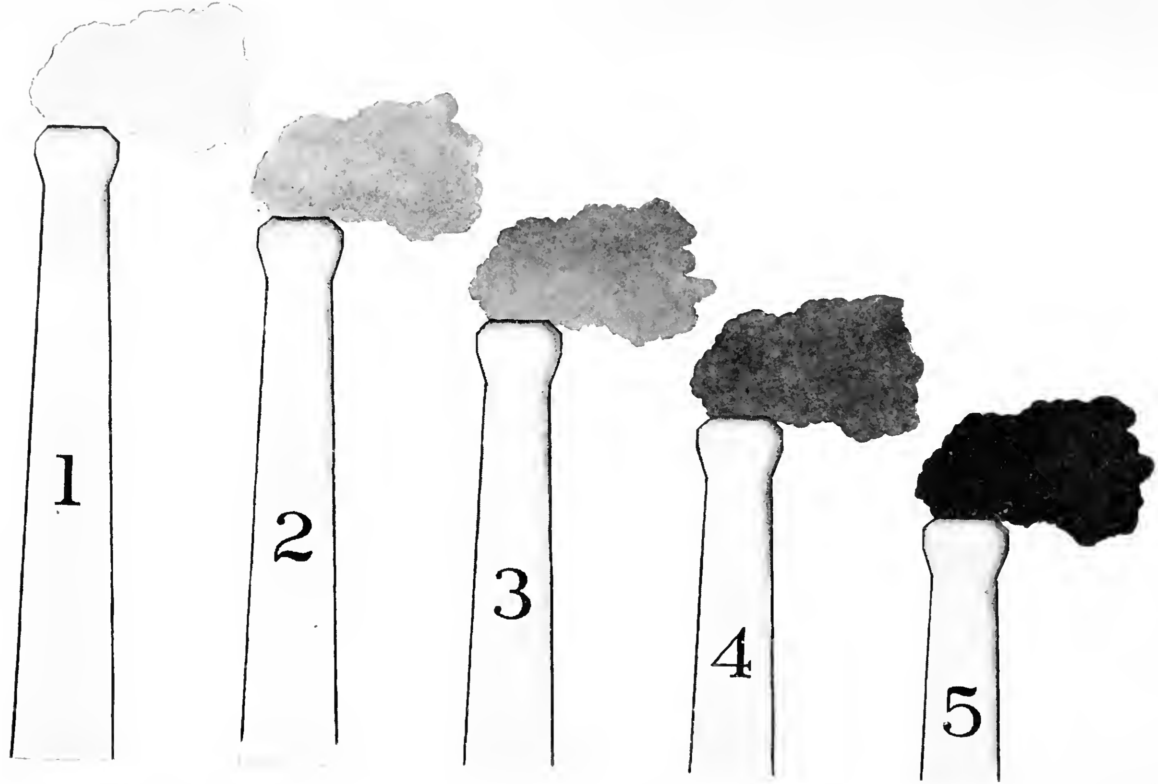

Fig. 2 Chimneys Illustrating Smoke Densities Approximating the Ringelmann Smoke Charts

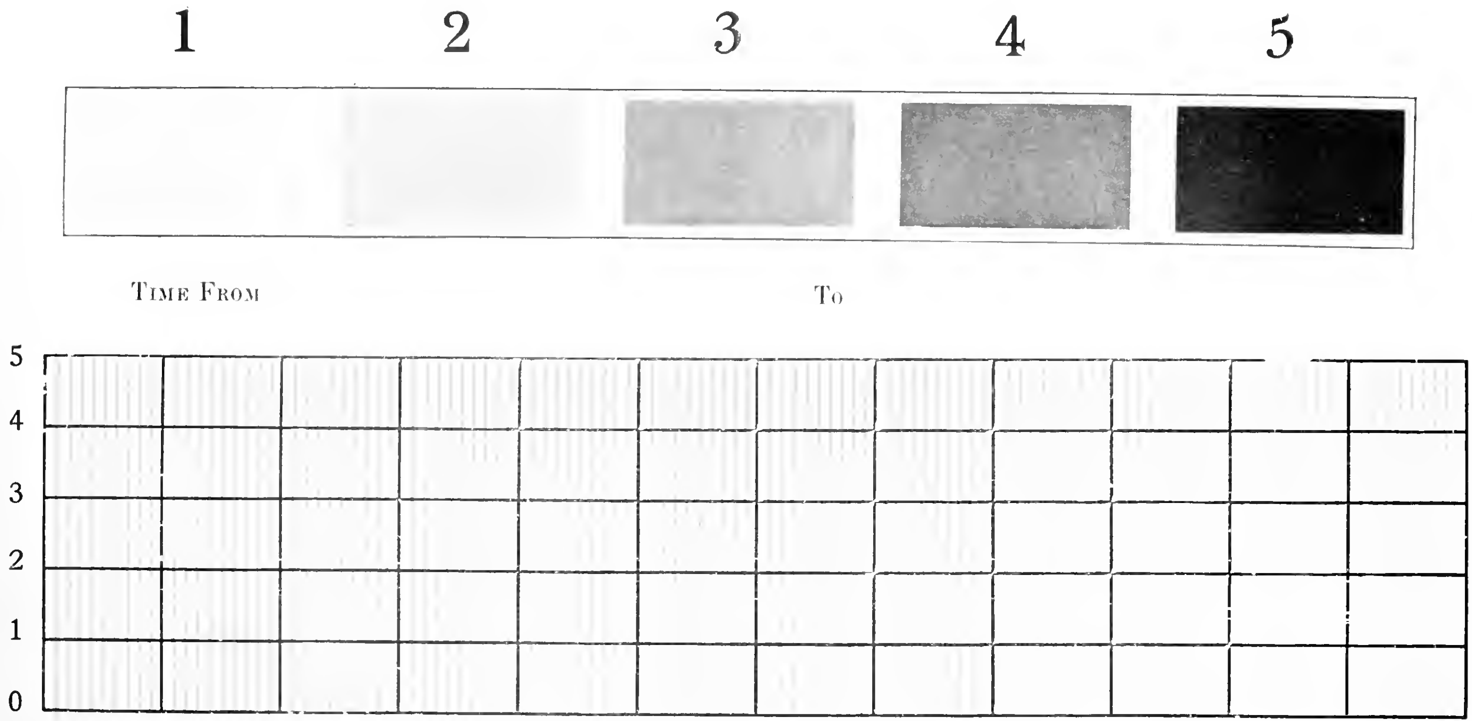

Fig. 3. Section of Smoke Chart Record

Boiler No. 3. Stirling standard boiler (150 lb.) equipped with Green chain grate stoker, usual baffling and combustion arches, capacity 260 H. P. Setting shown in Fig. 4. This unit can be run without smoke at capacities from 50 to 140 per cent.

Boiler No. 4. National water tube boiler (150 lb.), formerly equipped with Murphy furnace but now equipped with Green chain grate stoker: usual vertical baffling, capacity 250 H. P. This unit can be run without smoke at capacities from 50 to 120 per cent. When equipped with Murphy furnace, this unit was smokeless except when cleaning fires.

Boiler No. 5. Babcock & Wilcox standard boiler (150 lb.), equipped with Roney stokers, usual vertical baffling, capacity 220 H. P. Setting shown in Fig. 5. This unit when handled carefully can be run up to capacity without smoke above No. 2 on the smoke chart. It requires careful attention and at capacities above 100 per cent cannot be run without objectionable smoke. This boiler is an exact duplicate of unit No. 6.

Boiler No. 6. Babcock & Wilcox standard boiler (150 lb.), equipped with Roney stokers, special baffling making tile roof furnace. Boiler and stoker duplicate of unit No. 5. Capacity 220 H. P. Setting shown in Fig. 6. This unit can be run without smoke at capacities from 50 to 100 per cent.

Boiler No. 7. Stirling standard boiler (150 lb.) equipped with Stirling bar grate stoker, usual baffling and combustion arches, same as Boiler No. 3, capacity 260 H. P. This unit can be run without smoke at capacities from 50 to 140 per cent.

Boiler No. 8. Stirling standard boiler (150 lb.). Exact duplicate of boiler No. 7, capacity 260 H. P.

Boiler No. 9. (Engineering Experiment Station special test boiler), Heine standard boiler (150 lb.) equipped with Green chain grate, usual combustion arch, tile roof furnace, adjustable water back at bridge wall, capacity 210 H. P. Setting shown in Fig 7. This unit can be run without smoke at capacities from 50 to 140 per cent.

A study of the various units mentioned above reveals the fact that any one of the four well known types of boilers may be set over at least three well known types of automatic stokers and be operated

without objectionable smoke. The opinion of the writer, doubtless held by most engineers, is that the boiler has very little to do with the smoke problem, except perhaps that some types of boilers lend themselves more easily to the necessary furnace construction, which is of the utmost importance when perfect combustion is desired.

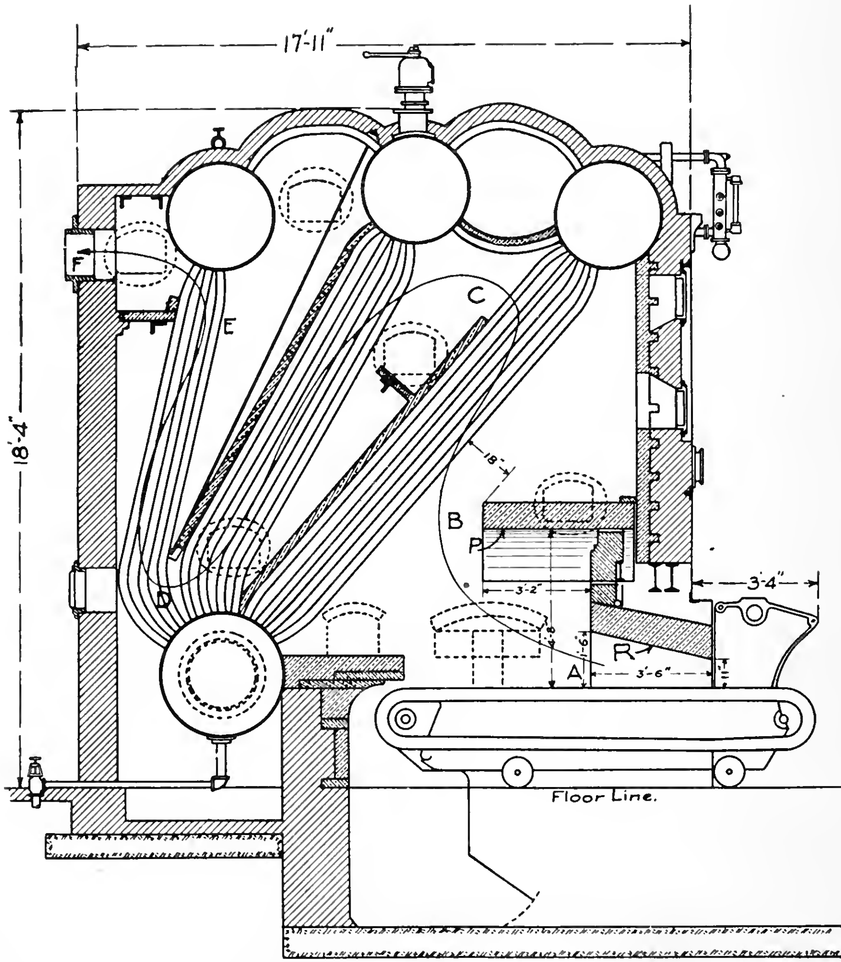

FIG. 4 STIRLING STANDARD 260 H. P. BOILER EQUIPPED WITH CHAIN GRATES

(Operates easily without smoke at capacities from 50 to 140 per cent).

DESCRIPTION OF THE SETTINGS SHOWN BY THE FIGURES

In the figures which accompany this article there are shown several types of boilers and furnaces that have been found suitable for burning Illinois coals without smoke. These settings have been operated under the immediate observation of the writer. Each figure is supplied with a title which is at the same time a description of the setting and an indication of the possibility of its smokeless operation under varying conditions of service. The drawings themselves are sufficient to illustrate the conditions that must be fulfilled to secure smokelessness when using boilers of these types under usual service capacities. The stack draft available for boilers No. 1 to 8 is 0.75 in. to 1.0 in. supplied by a brick chimney 150 feet high with an inside diameter of 6 feet. Boiler No. 9 is supplied with an economizer and

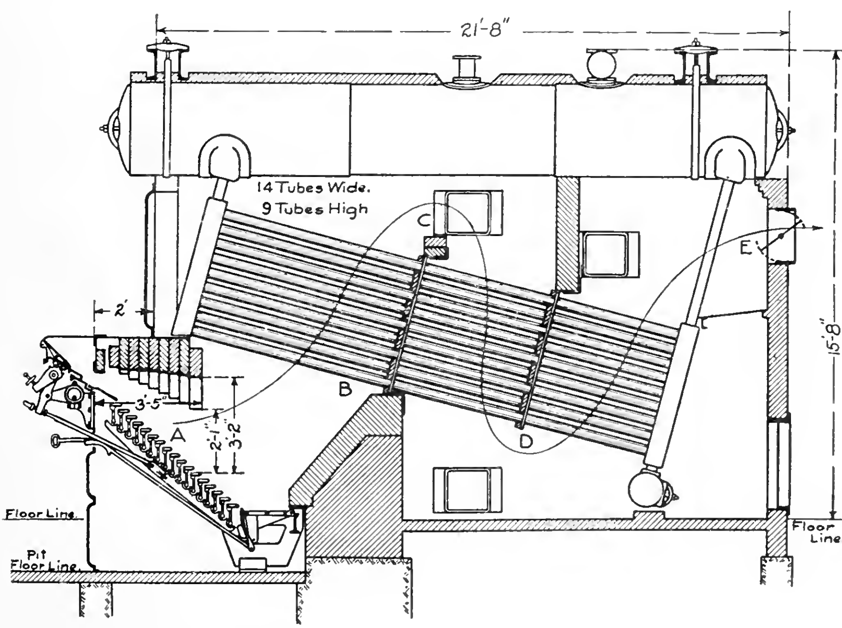

FIG. 5 BABCOCK & WILCOX 220 H. P. BOILER EQUIPPED WITH RONEY STOKERS, USUAL VERTICAL BAFFLING

(With careful handling may be run up to capacity without smoke above No. 2 on Smoke Chart; above 110 per cent capacity can not be run without objectionable smoke except by expert firemen.)

an induced draft fan permitting higher rates of combustion than are possible in the other settings.

In all of these settings it has been found necessary to pay particular attention to the coking arch under which the fresh charge of coal is being delivered. It seems to be true that over chain grates this arch should be inclined upwards more for a light than for a heavy draft. It is also believed that the arch of the Roney stoker should be kept well down toward the grates. The dimensions given in Fig 5 have given good results in these settings.

When Illinois coal is being burned in any furnace it is essential that the volatile products of combustion should be uniformly distilled from the coal and mixed with sufficient air at a high temperature. To accomplish this, particularly to maintain a high temperature, the mingling air and products of combustion must be kept away from the tubes or plates of the boiler which are comparatively cool, and which would therefore cool the gases before complete combustion had taken

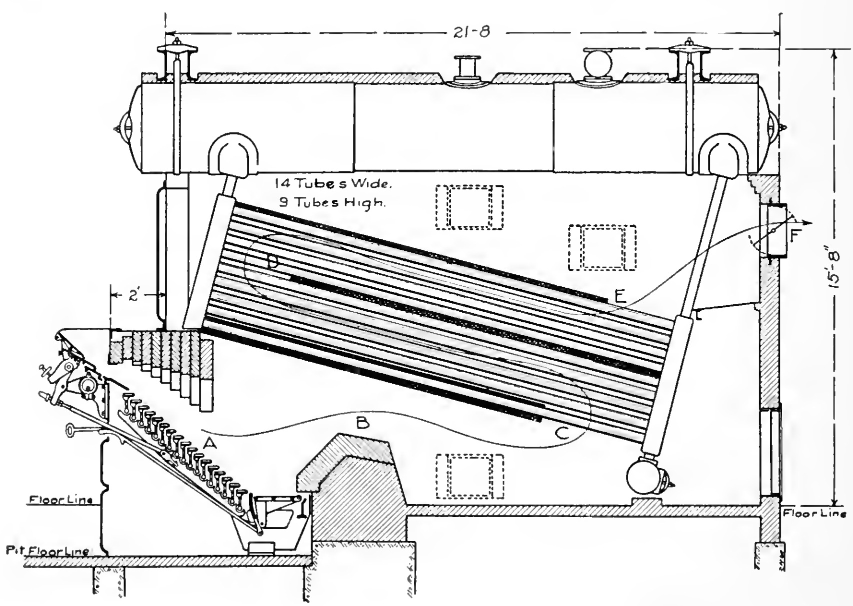

FIG. 6 BABCOCK & WILCOX 220 H. P. BOILER EQUIPPED WITH RONEY STOKER

(Setting as in Fig. 2, but arranged with different baffling, forming a tile roof furnace. This unit can be run at capacities from 50 to 100 per cent without smoke.)

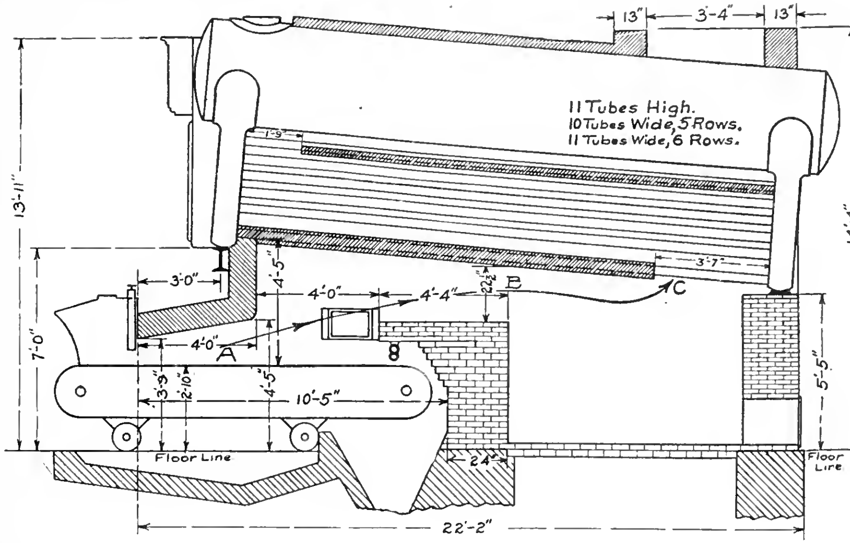

FIG. 7 HEINE STANDARD 210 H. P. BOILER EQUIPPED WITH GREEN CHAIN GRATE, COMBUSTION ARCH, TILE ROOF FURNACE, ADJUSTABLE WATER-BACK AT BRIDGE WALL

(This is the Engineering Experiment Station Boiler furnished with induced draft. It can be run easily without smoke at capacities from 50 to 140 per cent; almost impossible to make smoke with this setting under any condition of operation.)

place. It is for the reason just mentioned that such forms of furnaces as shown in Fig. 6, 7, and 8 are planned. Special forms of fire clay tile are designed to be hung on the water tubes of boilers that are directly over the fire. The tiles form the roof of the furnace and prevent the hot gases, which are still not properly mixed, from coming in contact with the cooler tubes which are surrounded by the tiles. These tiles are made in various forms, three types being shown in Fig. 9. The kind shown at C makes a smooth flat roof for the furnace and has been found very satisfactory.

The length of a tile roof furnace or the distance of flame traveled before reaching the cool tube surface must evidently depend upon the total volume of volatile products distilled from the coal on the grate in a given time, which must be mixed with the air supply before the cooling tubes are reached. The higher the coal is in volatile content or the higher the rate of combustion per square foot of grate area, the

longer will be this flame length. The coals that have been burned without smoke in the furnaces shown have had a combustile volatile content of from 30 to 40 per cent and they have been burned at a rate of from 16 to 40 lb. of coal per square foot of grate per hour. It will now be understood why such settings as shown in Fig. 5 cannot be depended upon for smokelessness. The cold tubes of the boiler are too near the flame, the temperature of the flame is reduced before combustion is complete and smoke results. There are coals low in combustible volatile matter that may easily be burned in such furnaces without smoke. In fact, when not forced, this furnace will burn many kinds of Illinois coals, but only with the greatest care have we been able to burn the usual grades of Illinois coals at desirable rates of combus-

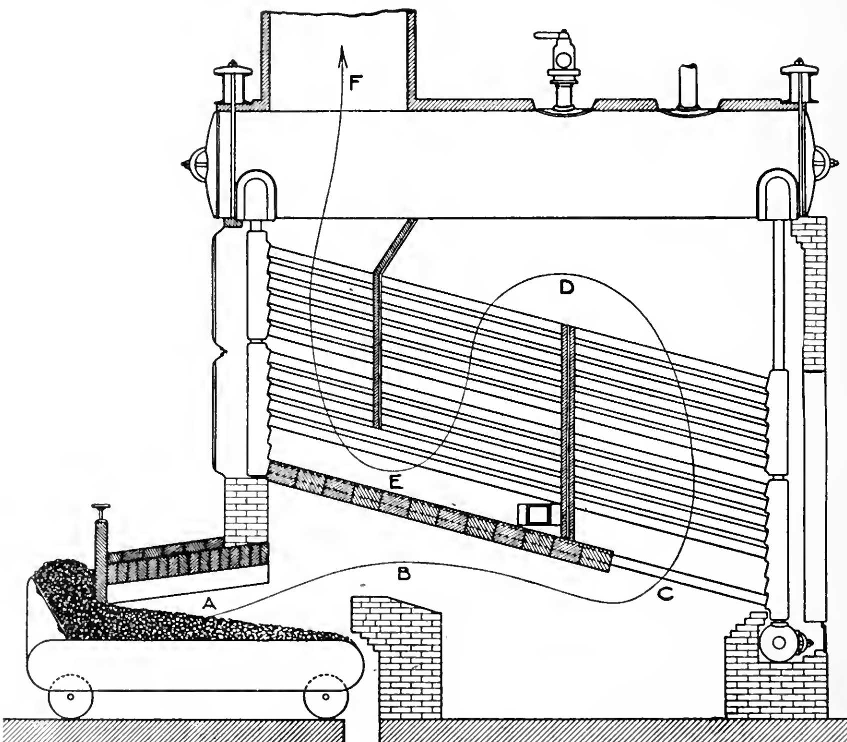

FIG. 8 SMOKE-PROOF STEAM GENERATOR DESCRIBED BY A. BEMENT, W.S. E. PAPER, OCTOBER, 1906.

(A satisfactory plan when proper attention is given to the draft available and to the areas of the gas passages.)

tion (24 to 30 lb.) without objectionable smoke, (No. 2 to 3½ on the smoke chart).

When the baffling shown in Fig. 6 was installed a series of smoke trials was arranged with this setting and the setting shown in Fig. 5. The results shown by these trials were disappointing and unsatisfactory. Lack of sufficient draft made it impossible to run setting Fig. 6 above its rated capacity. Under this condition there was little difference in the smoke from the two furnaces. This result suggests that changes in baffling of existing plants must be made with careful consideration of draft areas available or capacities may be cut down to an undesirable extent. The capacity possible with the setting shown in Fig. 6 proved to be about 90 per cent to 98 per cent while the capacity of the settings shown in Fig. 5 with the same coal was from 100 per cent to 120 per cent. The setting of Fig. 6 should prove satisfactory with higher draft pressures or by increased areas possible with a larger number of tubes in the vertical rows. From what has already been said about cool tubes, an inspection of the settings in Fig. 4, of a Stirling boiler over a chain grate stoker, might convey the impression that such a setting would produce smoke because of the absence of tile on the tubes below the path of the flame A B C. This setting has, however, proved to be a satisfactory and smokeless one. Looking at the progress of combustion through the side openings provided in the three settings of this character in the University plant, it is seen that the flame rolls along over the edges of the two arches shown and is by these arches completely mixed. No part of the tubes below the flame path A B C is enveloped by the flames; therefore the tubes have little cooling effect. It is also very evident that the lower ends of the tubes next the furnace fulfill their duty as heat transmitters by taking care of a very considerable part of the radiant heat which is available in large quantities at that point. Boilers of this type are now being manufactured at almost any desired height, the necessary capacity being furnished by increased width. They have proved very satisfactory, smokeless furnaces being easily arranged under them.

The Heine boiler set over a Green chain grate shown in Fig. 7 is the boiler installed by the Engineering Experiment Station for fuel tests with Illinois coals. This boiler is exactly like the Heine boiler used in the government fuel tests at St. Louis.* In this setting, how-

*The characteristic feature of these two settings is a tile roof furnace, originating in 1901 with W. L. Abbott, at the Harrison St. station of the Commonwealth Edison Co., Chicago.

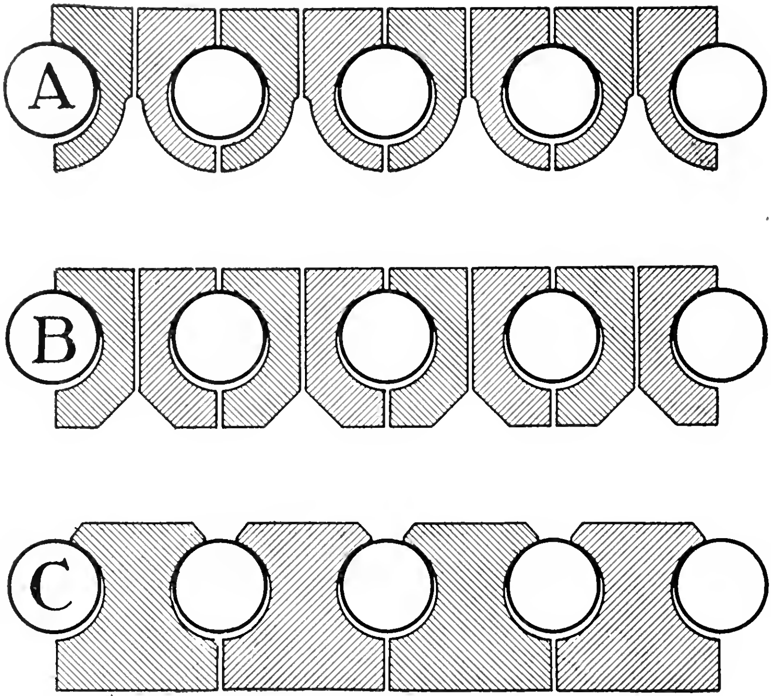

FIG. 9 THREE TYPES OF TILE ROOFS FOR BOILER FURNACES

ever, we have a stoker furnace while the government boilers were set with hand-fired furnaces, evidently necessary where coals from many sections of the country were to be tested. The setting shown in Fig. 7 is provided with an economizer and a large induced draft fan making high rates of combustion possible. This setting is smokeless under the many and varied conditions of operation which have thus far been applied to it. Over 100 trials of about 10 hours' duration of various kinds of Illinois coal have been made in this setting. In all of these trials the smoke record has been "No smoke all day." This is the setting to which the writer has referred in several recent talks by saying that in this setting it has been impossible to make smoke. In order to justify any such statement, attention is called to the results of a series of tests made with this setting for the express purpose of smoke production if such was possible under apparently adverse conditions.

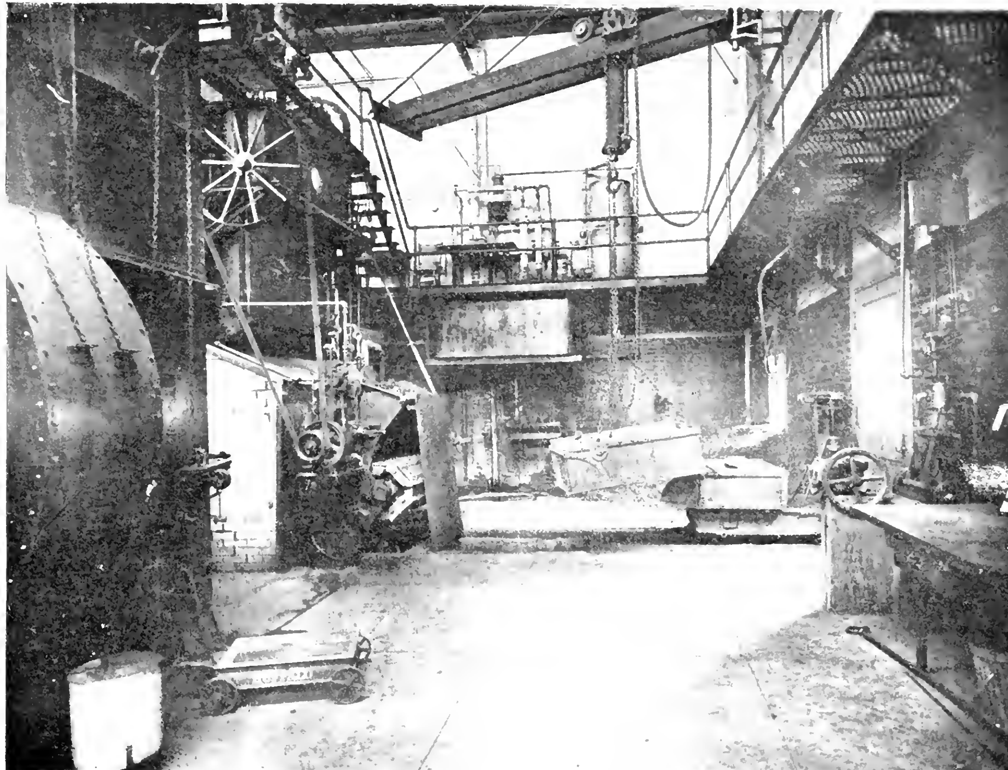

FIG. 10 GENERAL VIEW OF ENGINEERING EXPERIMENT STATION FUEL TESTING PLANT
210 H. P. HEINE BOILER, WEIGHING TANKS, ASH CAR AND HOIST, INDUCED DRAFT

Those who desire to grasp the simple yet fundamental principles of smokeless combustion for Illinois coals should thoughtfully consider just how this furnace fulfills the conditions of perfect combustion, as stated on page 15 in the words of Kent, Bement and the writer. A detailed account of the process in this furnace may well bear repetition here.

The fresh coal, fairly uniform in size, advances slowly from the hopper along on the grate toward the furnace where the temperature is very high. The combustible volatile matter is continually being distilled from the coal, more and more rapidly, but with much uniformity, while it is passing under the combustion arch. Some of the necessary air flows in through the coal in the hopper, more through the grate under the arch, but by far the most flows through the redhot coals on that part of the grate beyond the arch. This air is thus heated and made ready for combining with the volatile products flowing from beneath the arch, and all together mix and roll along on the bottom of the tiles forming the roof of the furnace.

The bottom row of boiler tubes is covered with suitably formed tiles, which prevent the still actively mingling gases from being cooled by coming in contact with the tubes, and so the combustion processes go on until completed before reaching C, a point before the gases pass in among the cooling tubes. The tiles in the adjoining rows touch each other so that no gases pass between them. In such a furnace as this the smoke problem is settled somewhere between B and C. When the total volume of combustible material distilled from the coal is quite large in a given interval of time, the flame length may reach to C, while for smaller volumes the flame may end at B. Thus it is that the flame length indicates the end of the combustion processes and gives us valuable information concerning the proportions of smokeless furnaces.

It is important in the operation of this or any form of mechanical stoker that abundant opportunity be afforded for inspecting the condition of the fires and the progress of combustion. .Appliances for continually indicating the composition of the escaping gases should be considered a necessity in all large and well managed plants.

The character of the draft apparatus available with this setting made it possible to make sudden changes in the rate of combustion. The rate of travel of the chain grate was easily adjusted by a throttle governor on the independent steam engine in driving the grate. The rate of combustion could be calculated very closely from the thickness

of the fuel bed and the rate of grate feed, by reference to the large number of tests already made with this unit. These special smoke tests were run on four different days, and on each day eight changes in condition of operation were made. The thicknesses of fire used were four, five, six and seven inches. The capacities varied from 60 to 150 per cent of the rated capacity (210 H. P.) of the boiler. The character and the size of the coal used are indicated in the tables. The results of these tests amply justify the conclusion that this type of furnace may be depended upon to operate even under adverse conditions without objectionable smoke, for out of a total of 32 tests in only six cases could any smoke be seen coming from the stack, and in three of these six smoke did not exceed No. 1 on the smoke chart. Where the most smoke was made, it was only No. 1½ and 2½, and here it will be observed that the draft had been suddenly reduced in the breeching, amounting to the condition of closing the damper with a brisk fire.

TABLE 1

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 5, 1907. Coal—Washed, Size No. 4[a].

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:10	9:00	9:30	9:56	1:00	1:30	2:00	2:35
Time, Stop		9:00	9:30	9:56	1:00	1:30	2:00	2:35	2:47
Thickness of Fuel Bed		4	4	4	4	4	4	4	4
Draft Pressure in Furnace		.092	.110	.180	.095	.098	.057	.050	.080
Draft Pressure in Breeching		.430	.600	1.260	.580	.500	.250	.090	.240
Lbs. Coal Burned per sq.ft.of Grate Surface as Fired		31.4	39.3	45.5	——	35.8	28.3	23.4	——
Do. Dry Coal		27.8	34.8	40.4	——	31.7	25.5	20.7	——
Mean per cent of Rated Capacity Developed		112	126	155	——	135	109	91	——
Flue Gas Temperature, °F		629	671	762	661	659	600	521	560
Temperature over grate		2500	2550	2620	——	2530	2390	2310	——
Temperature back of Bridge Wall		2470	2550	2710	——	2490	2390	2310	——
Per cent CO_2		12.0	12.8	12.2	——	12.8	12.8	14.4	——
Smoke		0	½	1	0[b]	0	1½	2½	0

(*a*) Moisture in coal as fired, 11.3 per cent; ash, 7.5 per cent.
(*b*) Grate stopped for repairs.

TABLE 2

Special Smoke Tests of Illinois Coal with a Chain Grate Stoker, Tile Roof Furnace and Heine Water Tube Boiler, with Varying Rates of Combustion. February 9, 1907.—Washed, Size No. 2[a].

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:03	9:00	10:00	11:00	12:00	1:00	2:00	3:00
Time, Stop		9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00
Thickness of Fuel Bed		6	6	6	6	6	6	6	6
Draft Pressure in Furnace		.126	.154	.178	.122	.12	.088	.060	.120
Draft Pressure in Breeching		.56	.73	.96	.56	.50	.23	.11	.35
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired		27.5	28.2	34.9	28.5	23.7	21.5	21.0	31.3
Do. Dry Coal		24.5	25.5	31.3	25.4	21.5	19.3	18.7	27.7
Mean per cent of Rated Capacity Developed		92	109	119	112	111	89	67	99
Flue Gas Temperature, °F		671	679	707	663	642	574	516	562
Temperature over Grate		2375	2485	2420	2340		2280	2235	2465
Temperature back of Bridge Wall		2305	2385	2340	2360		2210	2090	2475
Per cent CO_2		10.1	10.1	9.1	10.0	9.8	11.6	11.4	11.8
Smoke		0	0	0	0	0	$\frac{1}{8}$	0	$1\frac{1}{2}$[b]

(*a*) Moisture in coal as fired, 11 per cent; ash, 7.97 per cent.
(*b*) Much unconsumed coke forced over back end, thus increasing the ratio of volatile carbon in the fuel actually consumed.

The results of these experiments are given in Tables 1, 2, 3 and 4, and they certainly demonstrate the possibilities of smokeless combustion of some typical Illinois coals.

It is not within the scope of this bulletin to enter into any lengthy discussion of the results as shown by these tables. It should, however, be stated that this setting has been operated not only without smoke, but also with economy, as may be seen by inspection of Table 5. The complete record of the results of the economy tests made under this boiler will form the subject of a separate bulletin soon to be published.

Relation Between Capacity at Which Boilers are Driven and the Tendency of Their Furnaces to Smoke

There is a rate of driving a boiler furnace which, if exceeded, will result in producing smoke. This rate varies for different types of

furnaces and for the various methods of baffling or kinds of mixing piers used. It also varies for different kinds of coals. A strong draft will make a large air supply possible, and allow thicker fires or finer coal to be used. The possibility of sufficient air makes a furnace smokeless when an insufficient supply caused by a weak draft might cause the production of smoke. There is an always increasing tendency to drive boilers and furnaces a little harder. Boilers that were purchased for 1000 H. P. a few years ago are now being forced to 1400 and 1600 H. P. This means of course larger grate areas and a much higher rate of combustion per unit of grate area. As far as the boilers are concerned, they seem to be ready and willing to transmit about the same proportion of the heat available to the boiler as ever. It is doubtful if constructive furnace details have kept pace with the demands for the higher rates of combustion and at the same time have

TABLE 3

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 11, 1907. Coal—1½-inch Screenings. Ordinary Grade for Tests, 1, 2, 3, 4, 5[a]. Poor Grade for Tests, 6, 7, 8.

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:05	9:00	10:00	11:00	12:00	1:00	2:00	3:00
Time, Stop		9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00
Thickness of Fuel Bed		5	5	5	5	5	7	7	7
Draft Pressure in Furnace		.202	.252	.40	.23	.108	.302	.355	.58
Draft Pressure in Breeching		1.21	1.30	——	1.12	.23	1.48	1.21	——
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired		32.7	35.4	39.3	30.2	12.4	46.5	26.8	26.2
Do. Dry Coal		27.4	30.0	33.2	25.5	10.5	——	——	——
Mean per cent of Rated Capacity Developed		87	103	106	84	56	106	75	68
Flue Gas Temperature, °F		674	704	718	650	542	674	646	625
Temperature over Grate		2360	2400	2615	2489	2180	2530	2425	2485
Temperature Back of Bridge Wall		——	——	——	——	——	——	——	——
Per cent CO_2		6.8	7.6	6.6	7.2	6.2	7.0	4.7	4.3
Smoke		0	0	0	0	0	0	0	0

(a) Moisture in coal as fired, 14.23 per cent; ash, 15.4 per cent.

TABLE 4

SPECIAL SMOKE TESTS OF ILLINOIS COAL WITH A CHAIN GRATE STOKER, TILE ROOF FURNACE AND HEINE WATER TUBE BOILER, WITH VARYING RATES OF COMBUSTION. February 12, 1907. Coal—1½-inch Screenings, selected [a].

ITEM	Test No.	1	2	3	4	5	6	7	8
Time, Start		8:00	9:00	10:00	11:00	12:00	1:00	2:00	3:00
Time, Stop		9:00	10:00	11:00	12:00	1:00	2:00	3:00	4:00
Thickness of Fuel Bed		6	6	6	6	6	5	5	5
Draft Pressure in Furnace		.18	.25	.20	.10	.06	.195	.10	.05
Draft Pressure in Breeching		1.00+	1.5+	.93	.36	.21	1.20	.57	.15
Lbs. Coal Burned per sq. ft. of Grate Surface as Fired		28.3	32	28.3	23.9	16.8	31.0	26.5	22.6
Do. Dry Coal		24.2	27.3	24.2	20.4	14.3	26.5	22.6	19.3
Mean per cent of Rated Capacity Developed		89.8	85	91	85	74	100	92	80
Flue Gas Temperature °F		649	662	639	588	544	676	624	540
Temperature over Grate		2450	2525	2450	2435	2525	2305	2470	2490
Temperature Back of Bridge Wall									
Per cent CO_2		7	5.9	7	9.9	9.7	7.3	8.7	11.8
Smoke		0	0	0	0	0	0	0	0

(*a*) Moisture in coal as fired, 14.6 per cent; ash, 9.48 per cent.

provided efficient smoke preventing plans. In other words when boilers are forced much over 30 per cent of their rated capacity the probability of smoke from their furnaces rapidly increases. Nothing inherent in the boiler itself is at all responsible for smoking furnaces, for as elsewhere pointed out it is the total amount of volatile combustible evolved in the furnace per unit of time that imposes duties upon those constructive features of the furnace and combustion chamber which are designed to furnish the proper amount of suitably warmed air to the furnace and to provide for its effective mingling before the products of combustion reach the cooling surfaces of the boiler. It would seem necessary, therefore, that until further advances are made in furnace design and methods of operation, when a plant has reached the point of perhaps 140 per cent of its rated capacity, additional boilers ought to be added if only in the interest of a less amount of smoke. In

TABLE 5

Results of Evaporative Tests with Illinois Coals on a Chain Grate Stoker

Experiment Station Boiler with Tile Roof Furnace. Same Setting as Those Used for Special Smoke Tests in Tables 1 to 4.

Number........	47	50	91	96	107	127	131	134
2. Duration of Trial.....	8.32	8.32	8.30	8.25	8.10	7.02	8.15	7.37
3. Size and Condition of Coal(*1*)..........	$\frac{3}{4}-\frac{1}{4}$(w)	$\frac{3}{4}-\frac{1}{4}$(w)	$1\frac{1}{2}-0$ (*2*)	($1\frac{3}{4}-1$)	$1-\frac{3}{4}$(w)	$\frac{3}{8}-0$(w)	$\frac{7}{8}-\frac{3}{8}$(w)	$\frac{7}{8}-\frac{3}{8}$(w)
4. Per cent Moisture in Coal............	10.72	11.23	11.88	7.14	9.40	21.25	19.83	19.29
5. Per cent Ash in Coal..	7.31	7.64	16.89	8.42	8.21	12.58	7.68	7.19
6. Per cent Carbon in Ash Free, Dry Coal.	60.41	60.41	53.95	60.41	62.43	55.94	57.39	56.35
7. Per cent Volatile Matter in Ash Free, Dry Coal......	39.59	39.59	46.05	39.59	37.57	44.06	42.61	43.65
8. B. t. u. per Pound Coal as Fired.......	11898	11740	10036	12305	11922	9350	10274	10391
9. Thickness of Fuel Bed at Grate, inches.	6	4	6	5	6	5	5	5
10. Draft Pressure in Furnace, in. of water	0.127	0.085	0.258	0.112	0.120	0.387	0.117	0.161
11. Per cent CO_2 in Flue Gases (*3*)......	12.60	12.28	7.00	9.52	10.99	7.10	11.46	11.38
12. Excess Air Used, per cent......	43.54	47.16	150.1	83.4	56.4	143.8	57.4	57.6
13. Temperature of Escaping Flue Gases, °F	599.0	612.0	613.4	606.0	599.0	624.0	574.0	665.0
14. Dry Coal per sq. ft. Grate Surface, per hour	22.48	22.35	26.41	22.10	20.49	27.62	20.60	27.55

TABLE 5.—(Continued)

1. Trial Number	47	50	91	96	107	127	131	134
15. Carbon in Ash and Refuse, per cent of Dry Coal	4.00	3.95	2.23	2.23	1.56	5.46	1.75	1.89
16. Steam Pressure Gage	150.0	150.0	146.9	150.4	147.5	149.5	149.4	148.3
17. Per cent of Builders' Rated Horse-power Developed	109.4	109.3	103.1	101.8	99.9	99.5	101.4	133.8
18. Equivalent Evaporation from and at 212° F. per lb. Coal as Fired	8.24	8.23	6.52	8.12	8.37	5.38	7.49	7.44
19. Equivalent Evaporation from and at 212° F. per lb. Ash Free, Dry Coal	10.51	10.60	9.42	9.86	10.34	8.70	10.53	10.33
20. Efficiency of Boiler	69.93	70.75	64.60	65.32	69.00	60.18	71.76	70.61
21. Efficiency of Boiler including Grate	66.89	67.70	62.75	63.60	67.82	56.26	70.39	69.16

(*1*) Item 3—Size is given in inches. (w) refers to washed coal.
(*2*) Sixty per cent of this coal was below ¼ inch.
(*3*) The flue gases were free from carbon monoxide and smoke.

confirmation of this particular point the following discussion* is worth presenting. "The work at the government coal testing plant has been somewhat in the direction of smoke abatement, although the principal object of the work has been the determination of the value of different fuels for steaming purposes. Whenever we tested a soft coal we tried to eliminate the smoke. We have reduced the smoke 50 per cent or more, and often we burn soft coal without smoke. We have a good fireman, and he is watched all the time. Our furnace has a fire clay tile roof with a smooth lower surface, and a large combustion chamber; it is equipped with a plain grate of 40 sq. ft. We fire about fifty pounds of coal at a time on one-half of the grate area, and every two or three minutes. The furnace has three fire doors and we fire alternately in the front of the first and the third doors and in the rear of the middle door at one time, and then the rear of the first and third doors, and the front of the middle door at the next time. In this manner the distilled volatile matter is divided into three streams and this division facilitates its mixing with the hot air coming from the uncovered portions of the fuel bed.

"Another point in connection with the hand-fired furnace is that it is usually forced to burn more volatile matter than it was built for. We have often found that coal burned slowly, say at the rate of 20 pounds per square foot of grate area per hour, made no smoke at all. However, when the rate of combustion was increased to 26 pounds or more, smoke was produced, even though as great care was used in firing, and the firing was as frequent. This fact is in accordance with Mr. Bement's paper, where he states that the combustion space of a furnace is of a certain capacity, and that one should not try to burn more coal in it than the furnace was built for. The fact is that whenever a furnace is run above its capacity, it is bound to make smoke.

"I have recently noticed an interesting fact, that with a chain grate stoker in a Heine boiler furnace, no smoke was made when the rate of combustion was 42 pounds. If the same coal were burned in a hand fired Heine boiler furnace, smoke would probably be produced at the rate of combustion of 26 pounds. This seems to indicate that with the chain grate stoker more of the coal burns on the grate as fixed carbon and less of the combustible is driven off and burned as volatile matter, than is the case with a hand-fired furnace. This is probably due to the fact that with the chain grate stoker the coal is fed in grad-

*Jour. W. S. E., Dec. 1906. "Suppression of Industrial Smoke." A. Bement. Discussion by H. Kreisinger, U. S. G. S.

ually and is, therefore, heated gradually, while with the hand-firing, the coal is thrown on the top of the white-hot fire and is heated rapidly; this rapid heating is the cause of more combustible being distilled off as volatile matter and more smoke being produced.

"In conclusion I will say that the hand-fired furnace should be the last one to be considered for preventing smoke. In the first place it is rather expensive to operate, and the results are doubtful because too much dependence has to be placed on the fireman."

This discussion has been quoted because it definitely states a rate of combustion (20-26 lb.) as being about the limit for smokeless hand-firing in a certain type of furnace. It also gives good reasons why this rate may be nearly doubled on a chain grate stoker and not produce smoke. It might be well to point out, however, that while the average rate of combustion in the hand-fired furnace appears to be 20-26 lbs. for a short interval just after firing fresh coal, the rate is much higher, equal perhaps to the rate of 42 lb. of the chain grate stoker. It is entirely reasonable to suppose that furnaces will be planned that will provide for smokeless consumption of coal at much higher rates of combustion, but until they are available power plant owners should not be allowed to force boilers to such a point above capacity as will cause the furnaces to become troublesome smoke producers.

Special Mixing Devices, Piers, Wing Walls and Jets

The method of introducing the coal into the furnace will in all cases have much to do with the type of furnace which must be used to stop smoke. When the coal is fed into the furnace mechanically, as it is when stokers are used, one of the most essential elements of successful smoke prevention has been met, namely, slow and uniform gas evolution. When coal is fed by hand into a hot furnace, six shovelfuls more or less at one time, this same element has been ruthlessly neglected. The gas evolution can neither be slow nor uniform. It is also very doubtful if the proper amount of air at the right temperature will be supplied. It is to assist in correcting such known violations of correct methods of coal supply to furnaces that certain devices have been introduced which are intended to correct these initial mistakes. A steam jet is such a mixing device. When properly applied it does not let the volatile gases and air supply escape from the furnace until very intimately mixed. It has, however, two very serious objections, noise and

large steam consumption. From 5 per cent to 8 per cent of the steam made is often used in these jets. The success of the steam jet in preventing smoke, due almost entirely to its ability to properly intermingle the fuel gases and the air supply, immediately suggests the accomplishment of the same intermingling in other ways. Such ways have been devised. One of the early plans was proposed by Professor Kent in his wing wall furnace. Other plans have followed as typified by the Wooley furnace, and the Kuss mixing piers. These methods of mixing are efficient and economical and are especially to be considered in connection with hand-fired furnaces. The particular arrangement to be adopted will be determined by several factors, viz.; (a) The composition of the coal to be used. (b) Size of coal. (c) Method of firing. (d) The rate of gas evolution.

Smoke Prevention with the Horizontal Fire Tube Boiler

The horizontal fire tube boiler is still much in use in the smaller units of from 50 to 150 horse-power. It was brought into prominence in the early days of American steam boiler practice as the natural successor of the plain cylinder and flue boilers, all of which were externally fired. It soon became the standard type of boiler throughout manufacturing New England where in many places it still retains its position on account of its cheapness and its economical operation with all grades of anthracite and many grades of bituminous coals, especially those containing a high fixed carbon content.

With the coals just mentioned the combustion takes place mostly on the grate or at a short distance above it. Many plants have been installed with this type of boiler, in which the grate has been placed not more than 14 to 16 inches beneath the boiler. These plants have burned anthracite coal successfully. With the introduction of the West Virginia bituminous coals containing small amounts of volatile combustible matter the grates were lowered under this type of boiler to 24 and 30 inches with good effect. Still, with either coal, much the greater part of the heat was generated on or near the grate and the heat made available for transmission was largely radiant heat. The plates directly over the fire itself transmitted a correspondingly large part of the heat of the coal to the water in the boiler. The satisfactory performance of the fire tube boiler with eastern coals together with its availability made it naturally the boiler to be adopted by manufactur-

ers moving westward with the center of population. It is easily seen, however, that with Illinois coals carrying 30 to 40 per cent of volatile combustible matter and burned at rates which produce flame lengths of from 5 to 20 feet, this type of boiler as usually set is by no means adapted for the smokeless consumption of this kind of fuel. There is, in fact, no better method of producing dense black smoke with Illinois coal than to install a horizontal fire tube boiler with the usual furnace, and hand fire such a plant with run-of-mine coal. In such an outfit all the fundamental principles laid down elsewhere in this paper are disregarded. The method of introducing the coal directly into the hot furnace, in fine dust and large lumps, prevents slow or uniform distillation of the gases; the air supply through open doors, through holes in the fire, or through a fuel bed of varying thicknesses is neither correct in quantity nor is much of it properly heated; the mingling products of combustion come in contact with the cool surface of the plates of the boiler, reducing the temperature of the gases below the ignition temperature before combustion is completed.

Having in view these defects of the usual plan of operating the fire-tube boiler with Illinois coal, many ways suggest themselves by which these faults may be corrected. It is possible to burn Illinois coal without smoke with fire tube boilers, but the furnace requires special treatment and such settings are not common. The plans usually proposed are either low-set stokers or extended Dutch oven furnaces. When hand-firing is adopted the wing wall furnace or other form of mixing baffles or piers is of great assistance. With any of these devices careful firing is very necessary for satisfactory results. The twin brick arch furnace which keeps the gases away from the boiler plates altogether is an effective smoke preventive. Careful firing with low rates of combustion (12 to 16 lb.) per square foot of grate, assisted by automatically controlled air supply, will often enable these settings to be run so as to escape the fines of city smoke inspectors, but they can hardly be compared as to smokelessness with such settings as are illustrated in this paper. Horizontal tubular boilers are often adopted on account of their cheapness, and when such is the case the addition of any special furnace constructions or any special devices to aid in smoke prevention, is seldom given any consideration. From what has been said it is doubtless evident why this type of boiler is so frequently found to be one of our worst smoke offenders.

Burning Illinois Coal in Locomotive Boilers

The writer is compelled to admit that he does not know how to burn Illinois coal in a locomotive boiler under the usual operating conditions without making smoke. Careful firing is the most effective way of reducing the amount of smoke made, but no fireman can be found skillful enough to meet the exigencies which are always arising and to operate a locomotive boiler in service without smoke even 75 per cent of the time when using Illinois coal. It is not possible here even to enumerate the many devices which have been tried to prevent smoke production on locomotive boilers. The high rates of combustion on the grate of this boiler, often reaching 150 lb. and sometimes 200 lb. per square foot of area, produce temperatures which soon destroy all forms of fire resisting material or other constructions not backed up by water-jacketed metals. Were it not, however, for the many and sudden changes in the conditions of operation imposed by the very duties for which the locomotive is designed, all other obstacles might possibly be overcome and the locomotive become smokeless. Fortunately we can clearly see how to eliminate the smoking locomotive from the thickly populated districts by the use of the electric locomotive which now is able to meet the demands placed upon it for speed, acceleration, and tractive effort. It is also pointed out that the large power plant will now produce the electricity needed for this service with greater economy and at the same time burn Illinois coal without smoke.

How to Hand Fire Illinois Coals so as to Reduce the Production of Smoke

There are many small power plant units that are hand-fired which smoke badly. The construction of many of these furnaces is such that it is almost impossible to operate the plant without smoke. Still something might be done to reduce smoke if the fireman exercised more care in firing. Whatever can be done by the fireman in the way of properly introducing the fuel into the furnace is just so much gained and it relieves the auxiliary mixing devices or baffles if such exist from just so much work later on. The best method of hand-firing for smokelessness is also the best method for attaining economy. There are three generally recognized methods of hand-firing: (a) The Spreading, (b) The Coking and (c) The Alternate. The first is satisfactory and generally used for anthracite; the second for coking coals and the last

for non-coking coals. It is the alternate method that is best suited to Illinois coals. This method is described as follows. The fuel bed area is divided into equal parts two, four, or six depending on the size of the entire surface. The fresh coal is fired alternately on one-half of these areas at a time at such intervals as may be necessary to hold the steam pressure. Depending on the rate of driving, these intervals will vary from one to five minutes. For small areas first one-half the surface of the fuel bed is covered and then perhaps three minutes later the other half. This method allows much of the air supply to come through the bright fuel bed and thus become heated and suitable for mixing with the highly volatile content which is being rapidly driven from the freshly fired coal on the other side. Just because fresh fuel has been spread over one part of the fuel bed, the air most needed at that moment cannot as easily flow through it, and another part of the fuel bed should be left free for its passage at that time. When the fuel bed area is very large, some checker board system of firing may be adopted which, when alternately fired and left free for air passage, will result in a large reduction in the amount of smoke produced by the too common method of spreading the coal over the entire surface at each firing. It must not be forgotten that a large supply of warm air is needed immediately after fresh fuel is spread over a part or all of the fuel bed; this is best supplied as just explained, but it may be advantageous to provide for still more air by leaving the fire doors open slightly just after each firing. There are several devices on the market which provide for an air supply over the fire, which are turned on with the opening or closing of the fire door and which can be arranged to close at the end of any desired time depending upon the rate of driving and frequency of firing found desirable. The firing of small amounts of coal at frequent intervals produces less smoke than firing large amounts at longer intervals. The latter method, however, usually proves less tiresome to the fireman and is for that reason more frequently adopted.

The Distance Between the Boiler and the Grates

Having in mind the horizontal fire tube boiler, the distance from the bottom of the boiler to the grates should be from 30 to 34 inches. At this distance the flame from Illinois coals will sweep along the bottom of the boiler and much smoke will result. Still it must be borne in mind that a large part of the heat to be obtained from the burning of the fixed carbon part of these coals is transferred to the shell in the form

of radiant heat and for this purpose the grate should be near the boiler. While it is necessary in preventing smoke, that the flames be kept from the cooling surfaces of boilers, this cannot be accomplished by simply lowering the grates under a horizontal fire tube boiler, as the writer has unfortunately been incorrectly quoted as having stated. For boilers of this type some form of furnace extending partly or entirely in front of the boilers and either hand fired or fed by stokers of the Murphy type would undoubtedly furnish a satisfactory solution to the smoke problem. As elsewhere pointed out the smoke problem is not usually satisfactorily solved with Illinois coals and the horizontal fire tube boiler. The small unit hardly warrants an automatic stoker. Desire for a cheap plant prevents any special form of furnace and so it is that this kind of a setting frequently proves to be a troublesome smoker.

The Preparation of Coal for Smokeless Burning

When the coal fed into a furnace is fairly uniform in size it is much easier to burn it without smoke than when it is of different sizes. In all the settings described in this article as smokeless, the coal burned has been of such uniformity as to meet this requirement. The standard commercial sizes are all that are required, such as No. 1, 2, 3, 4, or 5. Take, for instance, the chain grate stoker; the very principle of its operation, complete consumption of the coal while it travels the length of the furnace, makes it very evident that if small pieces of coal are just consumed, the very large pieces will not be consumed. Just to what extent it will pay to size coal for regular use is not yet very clear, but experiments reported by Mr. W. L. Abbott in a paper before the Western Society of Engineers (Sept. 1906), makes it evident that the influence of variation in size of the fuel used is of much more importance than has heretofore been generally believed. In these tests the capacity as well as the efficiency of the plant tested increased rapidly with the size of the coal used between the average sizes of 0.12 inches and 0.30 inches, after which both these factors dropped again. The following table indicates the general results obtained.

Effect of variation in size of Illinois coal screenings.

Size in inches	Horse-Power	Efficiency
.15	350	53
.20	525	60
.25	650	65
.30	725	65
.35	625	63
.40	550	60
.45	500	58
.50	525	58

Whether these results are generally applicable or whether they apply only to the conditions existing in the operation of a single plant, it is difficult to say. The plant in which these tests were made corresponds so closely to the plants described in the paper that it would seem very desirable that those operating such plants should take advantage of the results obtained and be sure that the mere matter of inattention to size should not be responsible for a capacity or efficiency loss of from five to ten per cent.

The washing of coal, which removes a considerable part of the ash and sulphur, has proved very advantageous to many plants, especially where capacity has been an important consideration. The washing itself, however, does not make coal burn without smoke. As explained elsewhere the total volume of volatile combustible distilled per hour from each square foot of grate area must determine those furnace proportions necessary, with the various methods of coal supply to the furnace, which will with any kind of coal prevent smoke. The writer desires to mention in this connection that since he began to use washed nut coal in his hot water residence heater and in his kitchen range black smoke is seldom seen coming from his chimneys. Previous to the use of this coal the kitchen range pipe required cleaning at least once, sometimes twice each year. It is now three years since this pipe was cleaned. No soot now gathers on the underside of the stove lids as was formerly the case. A fire is easily maintained eight to twelve hours in the residence heater. Experiments with two types of residence heaters, which are now available for test purposes, are in progress by the Experiment Station, and it is hoped that more exact information concerning the relative value of various coals used in this kind of furnace will soon be available. The writer confidently believes that we shall soon know how to burn Illinois coals

without smoke in residence heating boilers as readily and surely as we now know how to burn it under power plant boilers.

Briquetted coal offers some opportunity for smoke reduction in certain kinds of furnaces, and certain railroads have reported favorably on its use inside city limits. It does not appear that it can compete with raw coal, certainly not in Illinois, if any consideration is to be given to the cost. There are conditions arising where the question of cost need not be considered,—such for instance as on naval vessels in time of war. For this reason a series of tests is now being arranged between the steam engineering department of the U. S. Navy and the technologic branch of the United States Geological Survey to determine the comparative value of raw and briquetted coal on board several types of naval vessels. In these tests the question of smokeless operation will be a question of careful consideration.

Powdered fuel has been used with much success in places where the coal has not been too high in volatile combustible content, and where the cost of the coal ordinarily used exceeded five or six dollars a ton. Powdered fuel can be burned without smoke and it can be burned with excellent economy. It cannot, however, be cheaply reduced to a powder.

The writer will welcome suggestions relating to the smoke problem from engineers throughout the country, also drawings, blueprints, etc., and complete and reliable data pertaining to smokeless furnace construction.

Bulletin No. 1. Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (Out of print.)

Circular No. 1. High-Speed Tool Steels, by L. P. Breckenridge. 1905.

Bulletin No. 2. Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.

Circular No. 2. Drainage of Earth Roads, by Ira O. Baker. 1906.

Bulletin No. 3. The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (Out of print.

Bulletin No. 4. Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.

Bulletin No. 5. Resistance of Tubes to Collapse, by Albert P. Carman. 1906.

Bulletin No. 6. Holding Power of Railroad Spikes, by Roy I. Webber. 1906.

Bulletin No. 7. Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906.

Bulletin No. 8. Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (Out of print).

Bulletin No. 9. An Extension of the Dewey Decimal System of Classification Applied to Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.

Bulletin No. 10. Tests of Plain and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 11. The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907.

Bulletin No. 12. Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 13. An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.

Bulletin No. 14. Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907.

Bulletin No. 15. How to Burn Illinois Coal Without Smoke, by L. P. Breckenridge. 1907.